

Di-Boson Production at Hadron Colliders



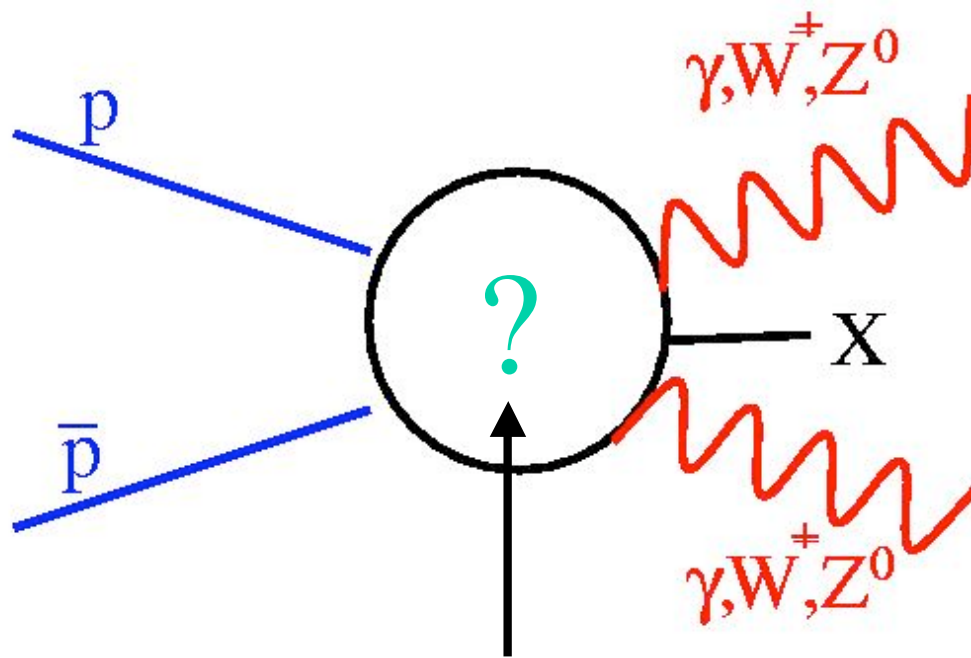
Beate Heinemann, University of Liverpool

- The Standard Model and Beyond
- Tevatron and the LHC
- $\gamma\gamma$
- $W\gamma$ and $Z\gamma$
- WW, WZ, ZZ
- Wh
- Summary and Outlook

Northwestern University - Seminar Oct. 4th 2004

Di-Boson Production: What's that?

Associated production of ≥ 2 gauge bosons of electroweak interaction



$$pp \rightarrow \gamma\gamma, W\gamma, Z\gamma, \\ WW, WZ, ZZ \\ + X$$

Something happens

The Standard Model of Particle Physics

-3 generations of quarks and leptons interact via exchange of gauge bosons:

-Electroweak $SU(2) \times U(1)$: W, Z, γ

-Strong $SU(3)$: g

-Symmetry breaking caused by Higgs field

⇒ Generates Goldstone bosons

⇒ Longitudinal degrees of freedom for W and Z

⇒ 3 massive and one massless gauge bosons

Gauge Bosons

Particle	Mass (GeV/c ²)	Force
Photon (γ)	0	Electroweak
W^\pm	80.450	Electroweak
Z^0	91.187	Electroweak
Gluons (g)	0	Strong

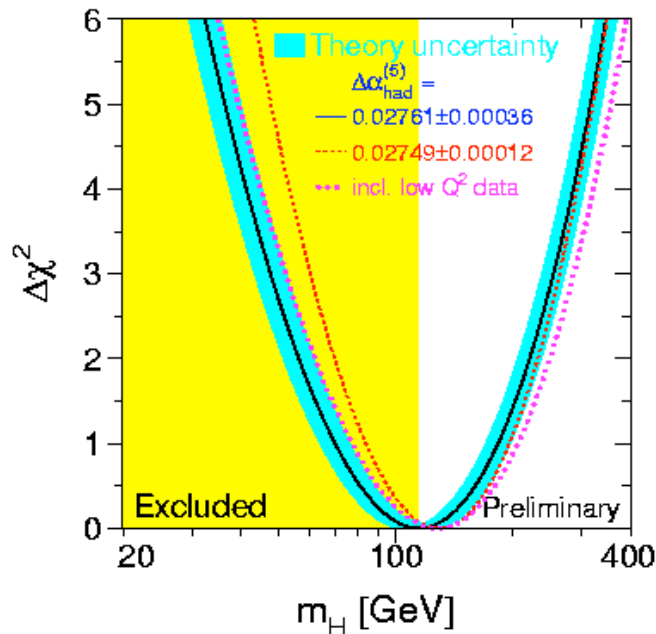
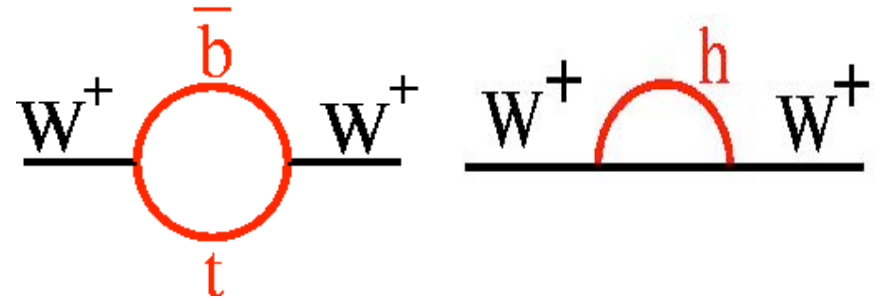
Higgs Boson

- Vacuum quantum numbers (0^{++})
- Couples to mass

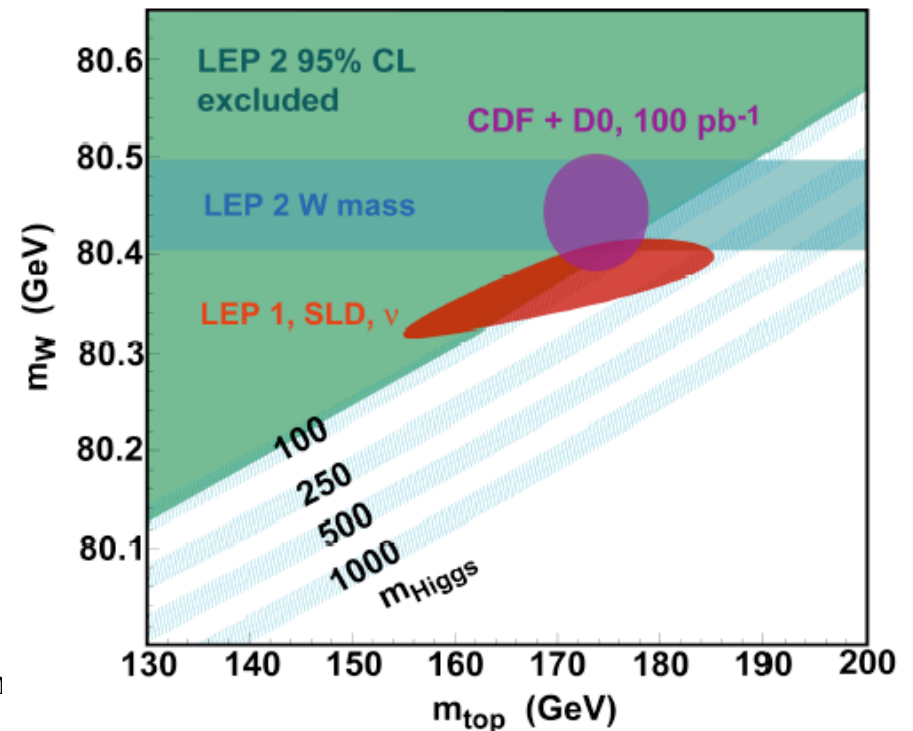
The Higgs boson: what do we know?

- Precision measurements of
 - $M_W = 80.412 \pm 0.042 \text{ GeV}/c^2$
 - $M_{\text{top}} = 178.0 \pm 4.3 \text{ GeV}/c^2$
- Prediction of higgs boson mass within SM due to loop corrections
 - Most likely value: 114 GeV
- Direct limit (LEP): $m_h > 114.4 \text{ GeV}$

m_W depends on m_t and m_h



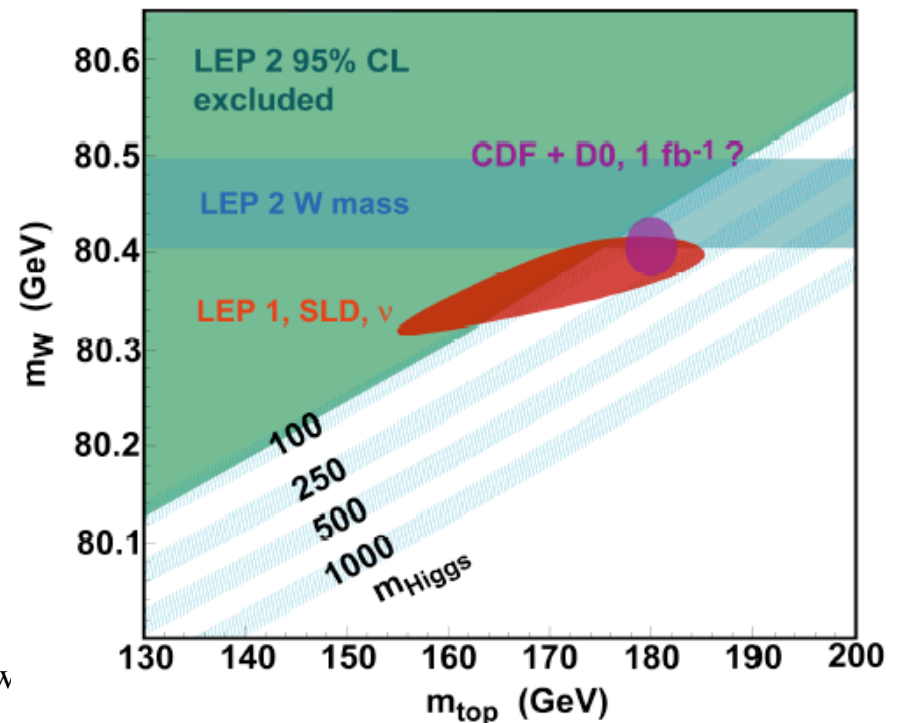
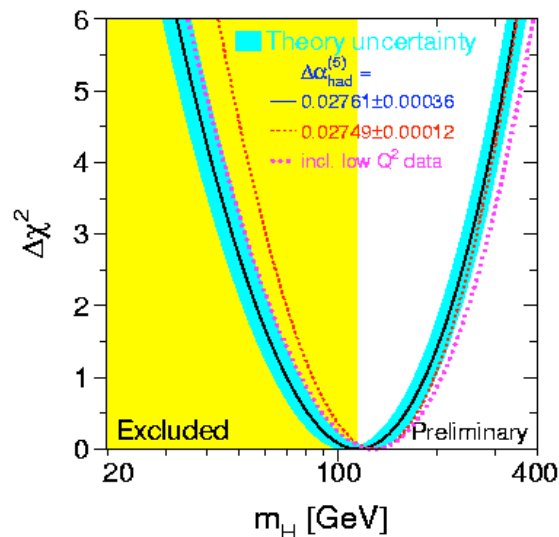
Heinemann - North



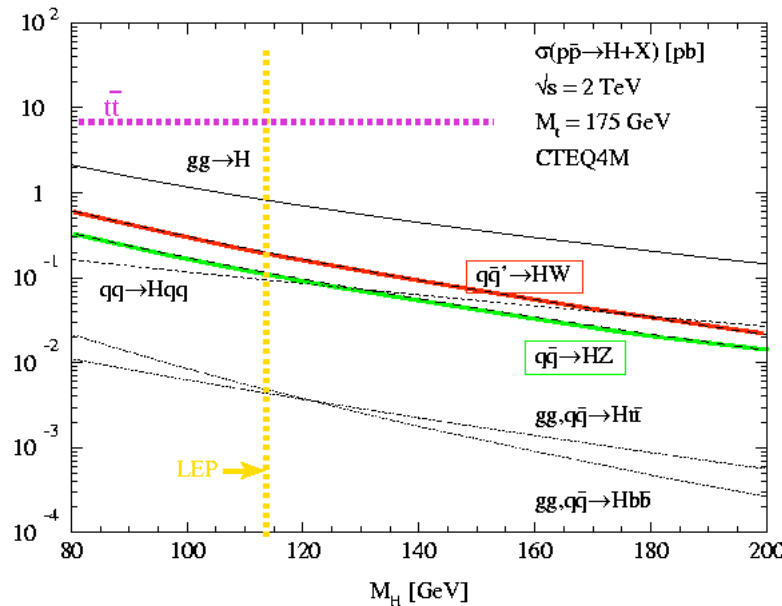
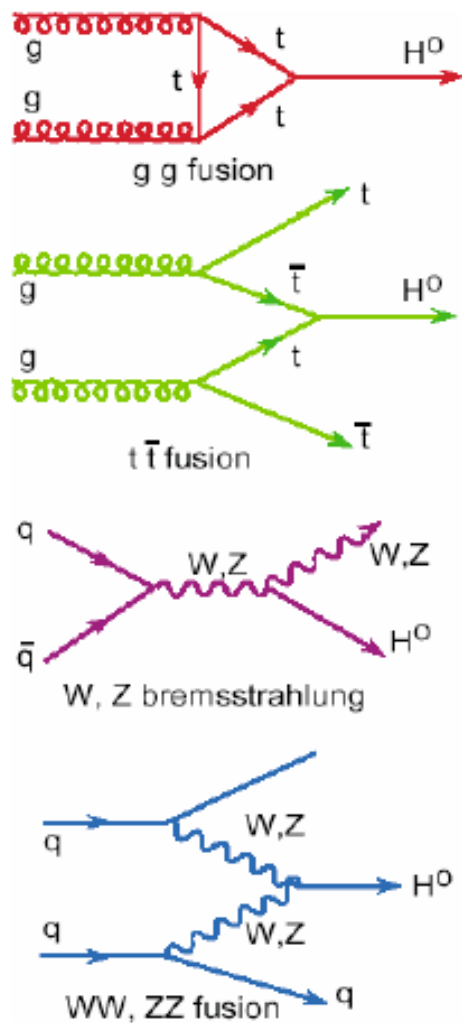
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Better prediction with expected improvements on W and top mass precision

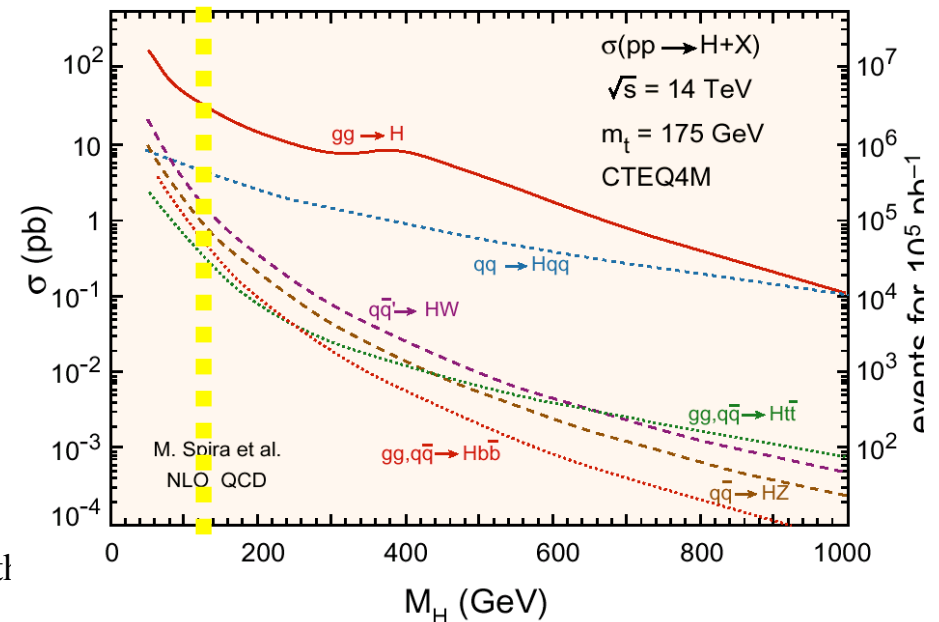


Higgs Production: Tevatron and LHC



Tevatron

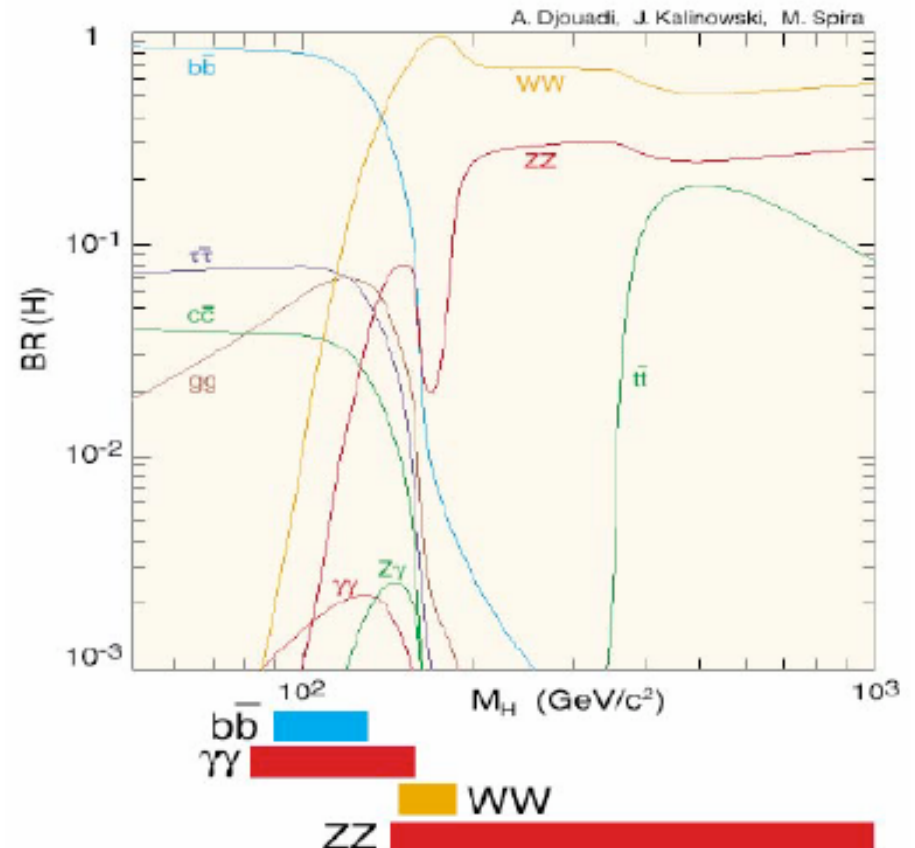
LHC



Dominant Production: $gg \rightarrow H$,
 subdominant: HW , $Hq\bar{q}$

Higgs boson decay

- Depends on Mass
- $M < 130 \text{ GeV}$:
 - $b\bar{b}$ dominant
 - $\tau\tau$ subdominant
 - $\gamma\gamma$ used at LHC
- $M > 130 \text{ GeV}$
 - WW dominant
 - ZZ cleanest



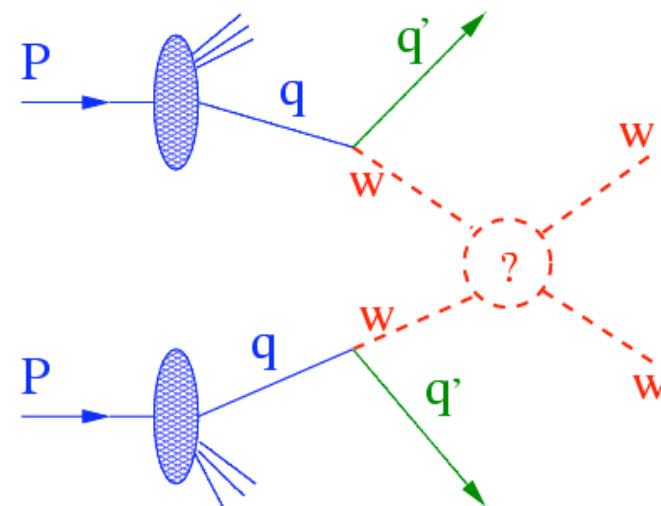
=> di-boson decays most promising!

What if there is no Higgs?

- $W_L W_L$ cross section would violate unitarity since amplitude perturbative expansion in energy (s): $\sigma \sim s^2/v^2 + s^4/v^4 \dots$

- Need either a Higgs boson with $m_h < 1$ TeV or some new physics (e.g. SUSY, Technicolor)

- Tevatron and LHC probe relevant scale of 100 GeV - 1 TeV!



=> We will find something (higgs or more extraordinary) in the next 10 years!

Beyond the Standard Model

■ Why not the Standard Model?

- Hierarchy problem: $m_h \ll m_{Pl} \Rightarrow$ new physics at TeV scale
- Most Dark Matter in our universe unaccounted for
- No unification of forces ...+ many more

■ What is beyond the Standard Model?

- Supersymmetry (SUSY):
 - rather complex (>100 parameters)
- Extra Dimensions
- Techni- and Topcolor
- Little Higgs
- Extended Gauge Groups or Compositeness:
 - Z' , excited fermions, leptoquarks, ...

New particles heavy \Rightarrow
At high energy colliders

- Direct production
- Indirect contributions

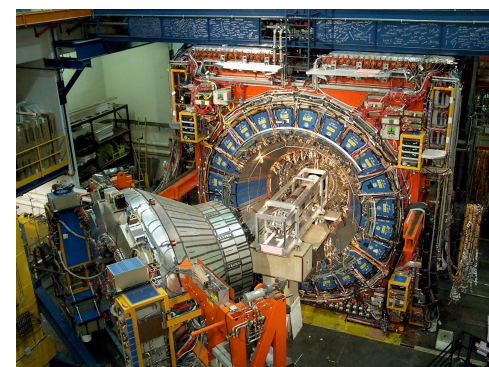
Tevatron Run II

- Upgrade completed in 2001

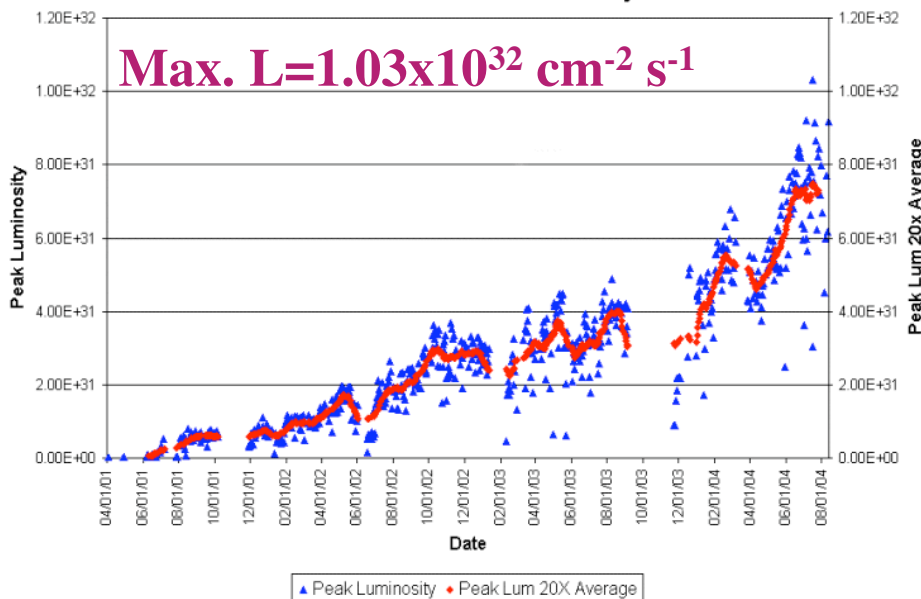
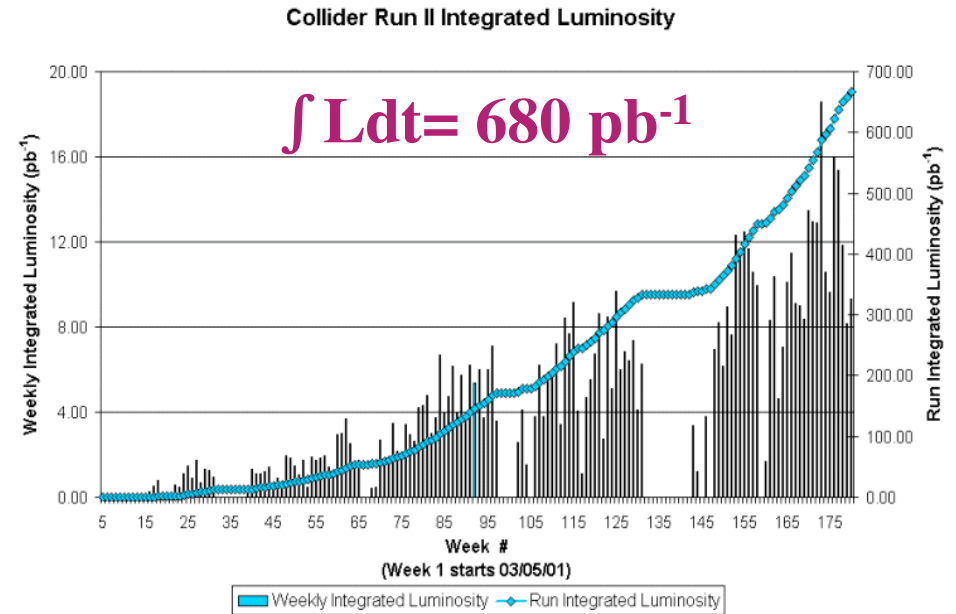
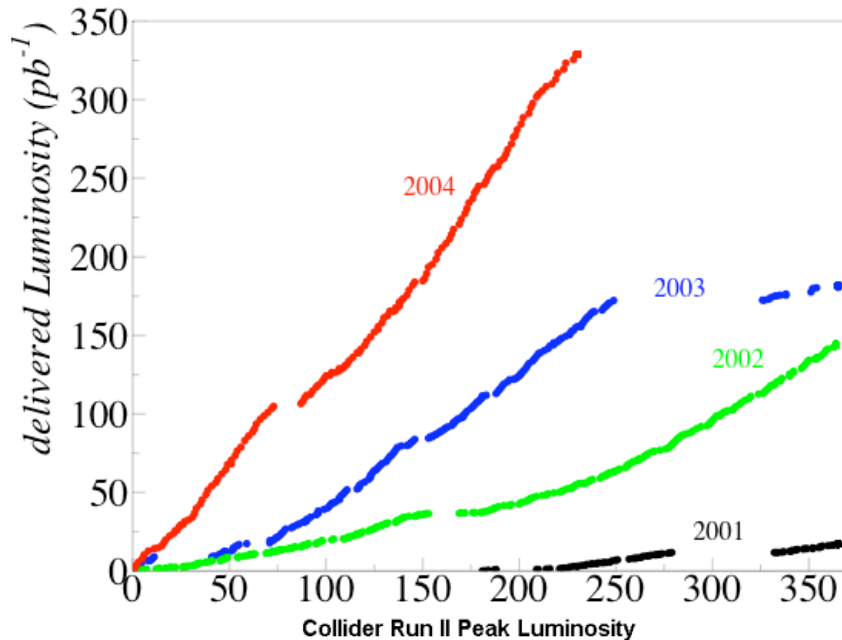
- Accelerator:

	$\sqrt{s}(\text{TeV})$	$\Delta t(\text{ns})$	$L(\text{cm}^{-2} \text{s}^{-1})$
Run I	1.8	3500	2.5×10^{31}
Run II	1.96	396	1.0×10^{32}

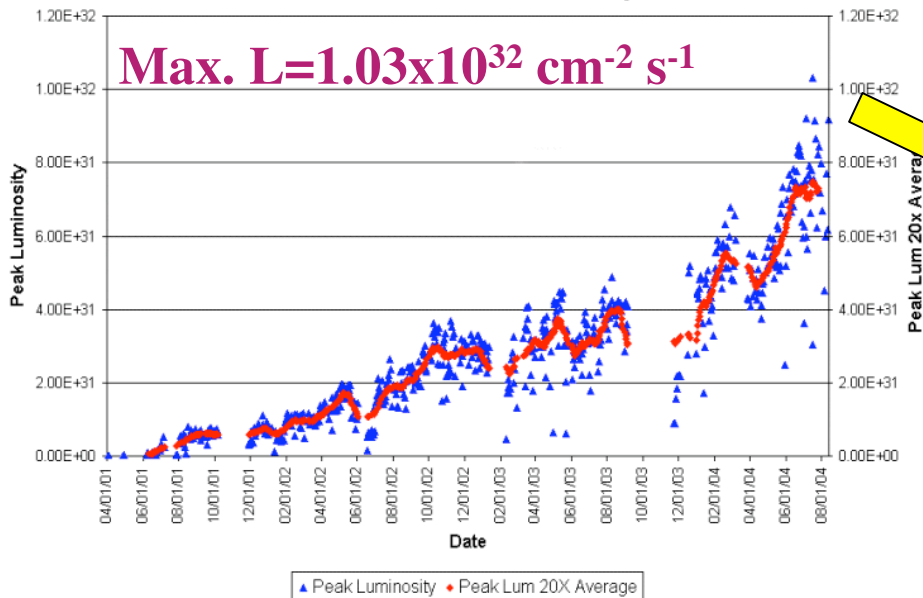
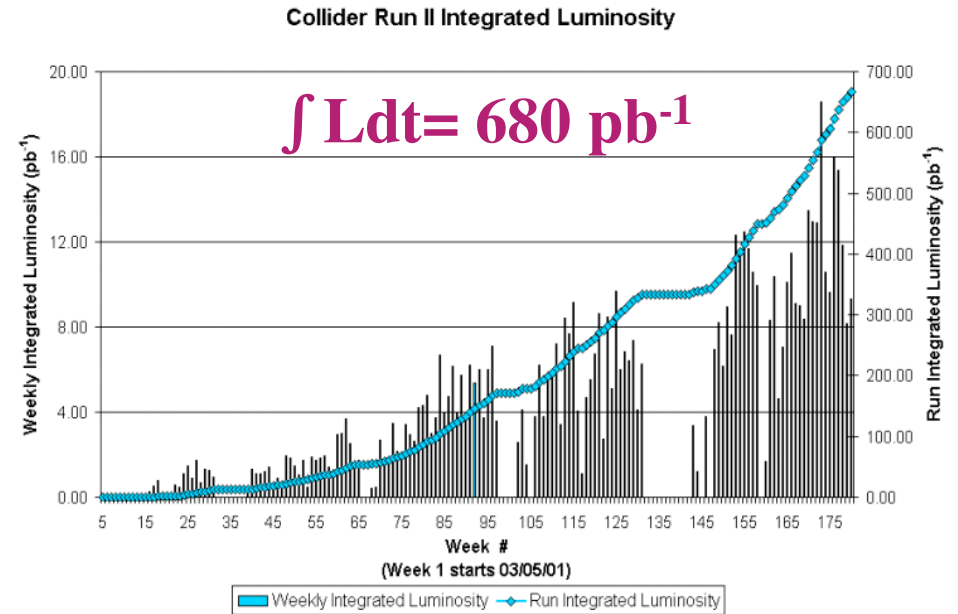
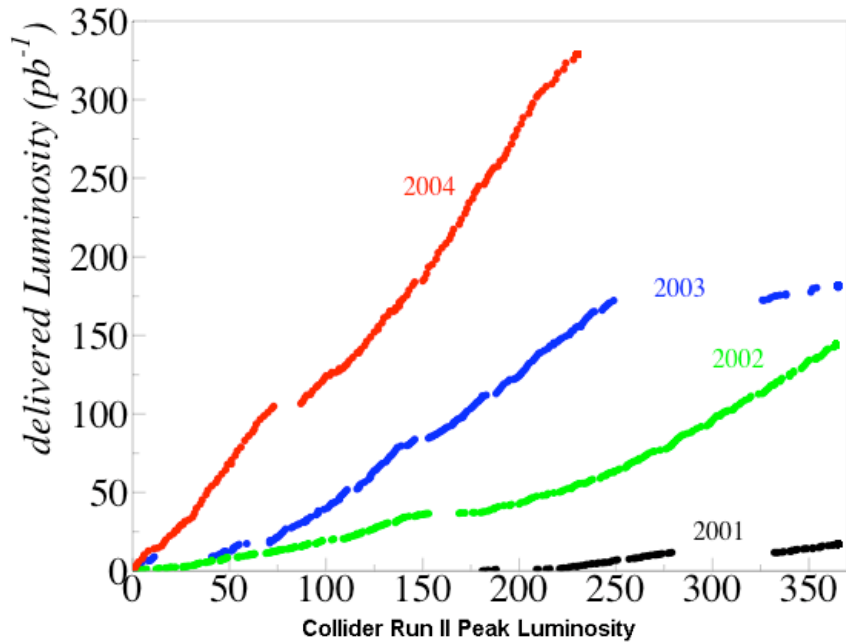
- Experiments CDF and D0:
 - New tracking systems
 - New RO electronics+trigger
 - Many other substantial new components and upgrades
 - Data taking efficiency > 85%
- Will mostly focus on CDF but show also some D0 results



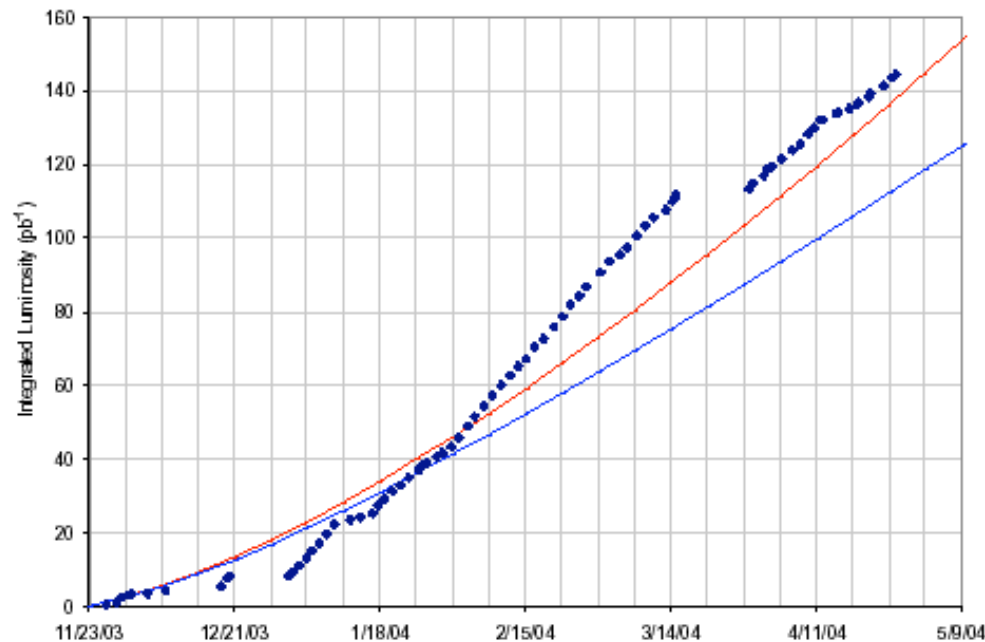
Tevatron Performance



Tevatron Performance



Tevatron: Expected Performance



— design
— base
■ measured

projections based on above curves

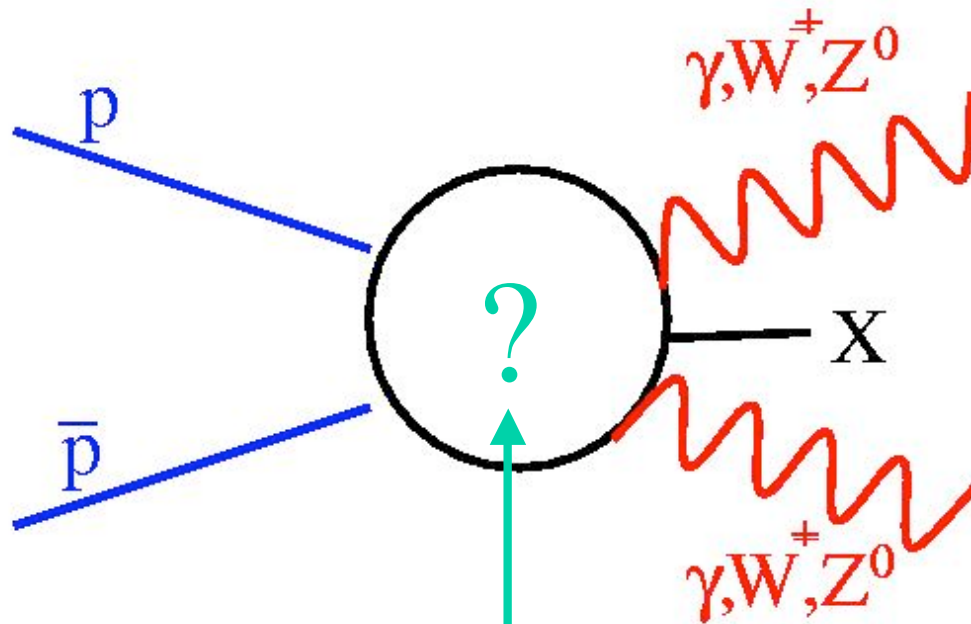
Integrated Luminosity (fb^{-1})				
	Design Projection		Base Projection	
	per year	Accum- ulated	per year	Accum- ulated
FY03	0.22	0.30	0.20	0.28
FY04	0.38	0.68	0.31	0.59
FY05	0.67	1.36	0.39	0.98
FY06	0.89	2.24	0.50	1.48
FY07	1.53	3.78	0.63	2.11
FY08	2.37	6.15	1.14	3.25
FY09	2.42	8.57	1.16	4.41

Beyond the Tevatron: LHC



- pp-collider at CERN
- Center-of-mass energy:
14 TeV
- Starts operation in 2008
- 3 years "low" luminosity:
10 fb⁻¹ /yr
- High luminosity:
100 fb⁻¹ /yr

Di-Boson Production: Why?

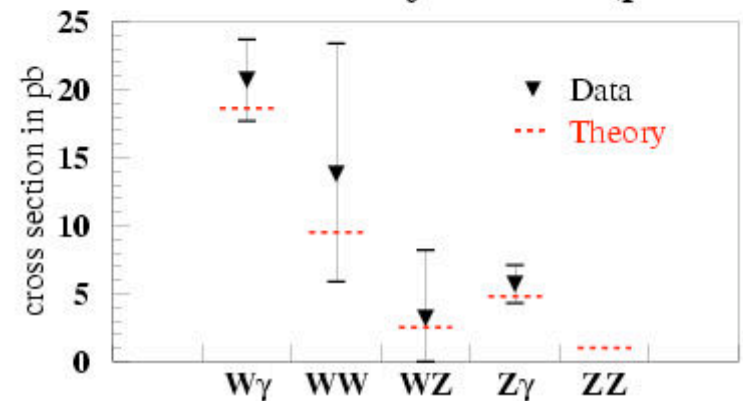


Something happens

Precision of Run I measurements
limited

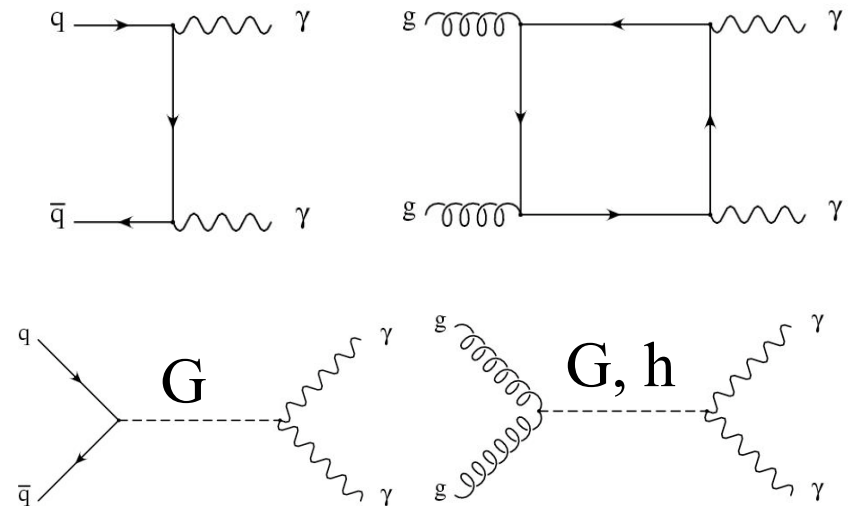
- SM precision tests
- SUSY
- Large Extra Dimensions
- Higgs
- Run I anomalies

Diboson cross sections from CDF (preliminary)

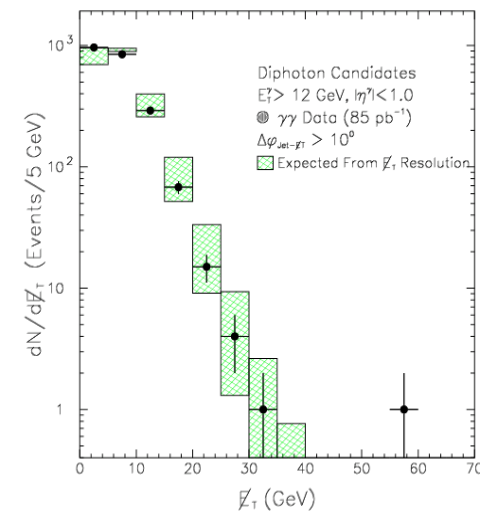
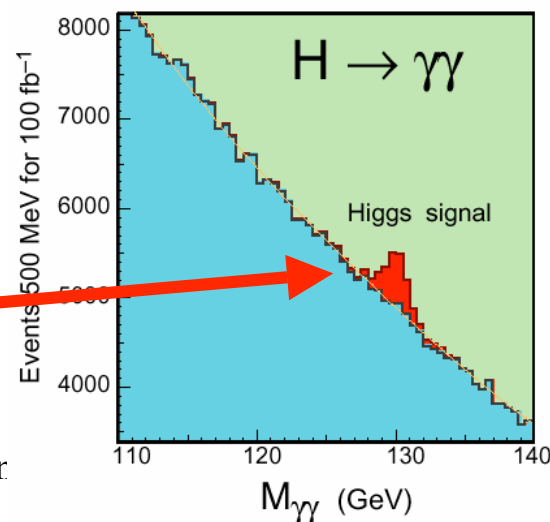


Di-Photon Production

- SM couplings small
- Ideal for New Physics Searches:
 - Large Extra Dimensions:
 - Graviton exchange?
 - Present sensitivity about 900 GeV
 - Run II: sensitivity about 2 TeV
 - Higgs $\rightarrow \gamma\gamma$:
 - BR small in SM but discovery channel at LHC
 - Enhancements predicted in some BSM theories ("bosophilic Higgs")
 - Extraordinary events with 2 photons and transverse momentum imbalance(?)

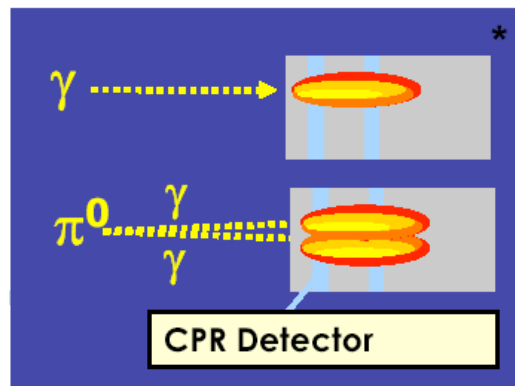


Example LHC signal
(CMS: 3 yrs)

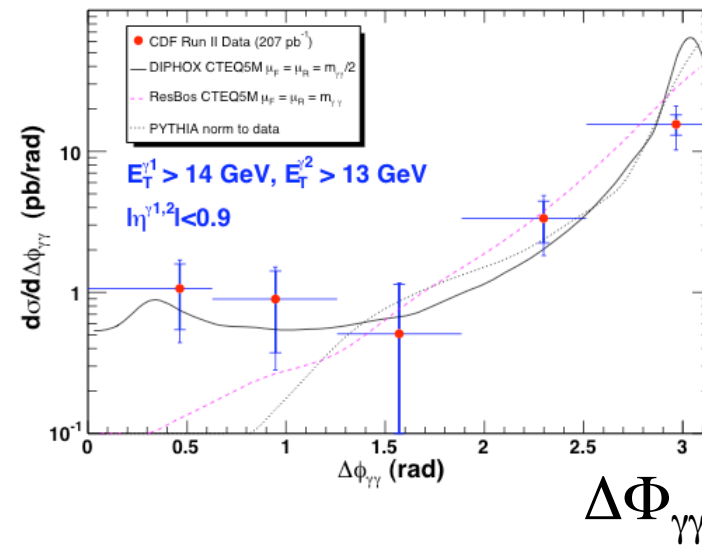
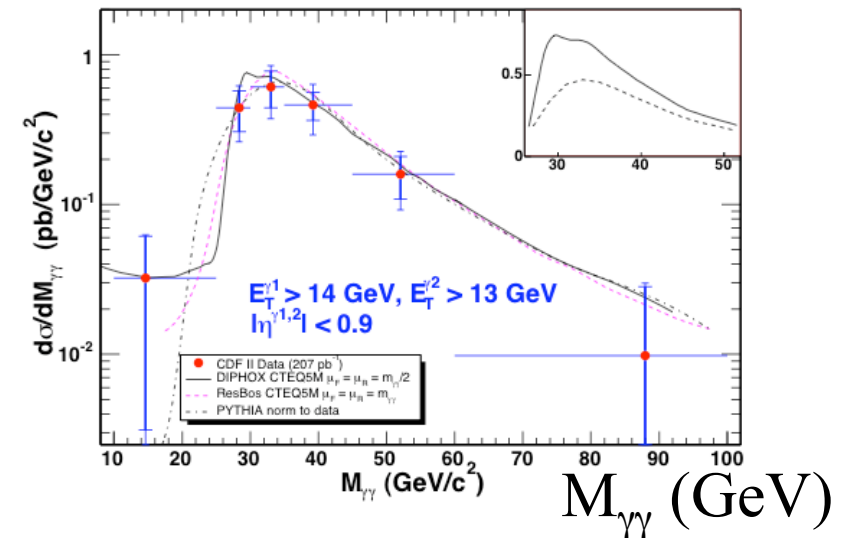


Di-Photon Cross Section

- Select 2 photons with $E_T > 13$ (14) GeV
- Statistical subtraction of BG (mostly $\pi^0 \rightarrow \gamma\gamma$)

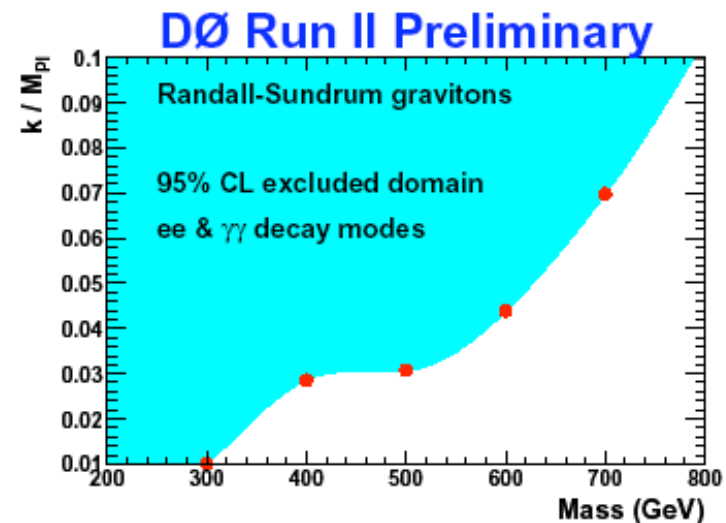
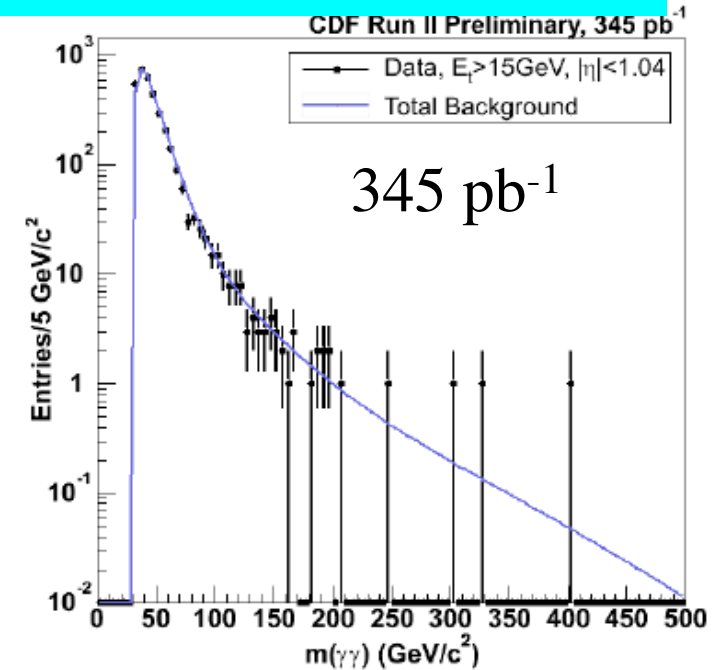


- Data agree well with NLO
- PYTHIA describes shape (normalisation off by factor 2)



Randall-Sundrum Graviton

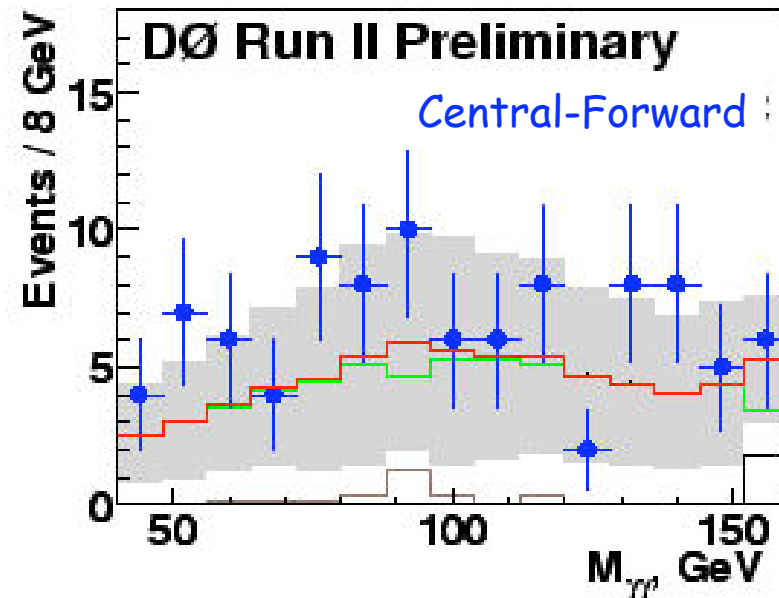
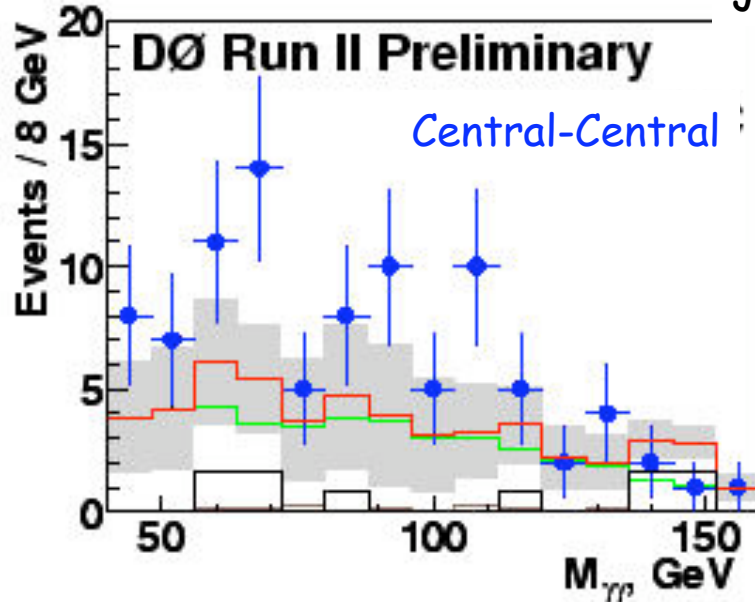
- Analysis:
 - D0: combined ee and $\gamma\gamma$
 - CDF: separate ee , $\mu\mu$ and $\gamma\gamma$
- Data consistent with background
- Relevant parameters:
 - Coupling: k/M_{Pl}
 - Mass of 1st KK-mode
- World's best limit:
 - $M > 785 \text{ GeV}$ for $k/M_{Pl} = 0.1$



DØ: Non-SM Light $H \rightarrow \gamma\gamma$

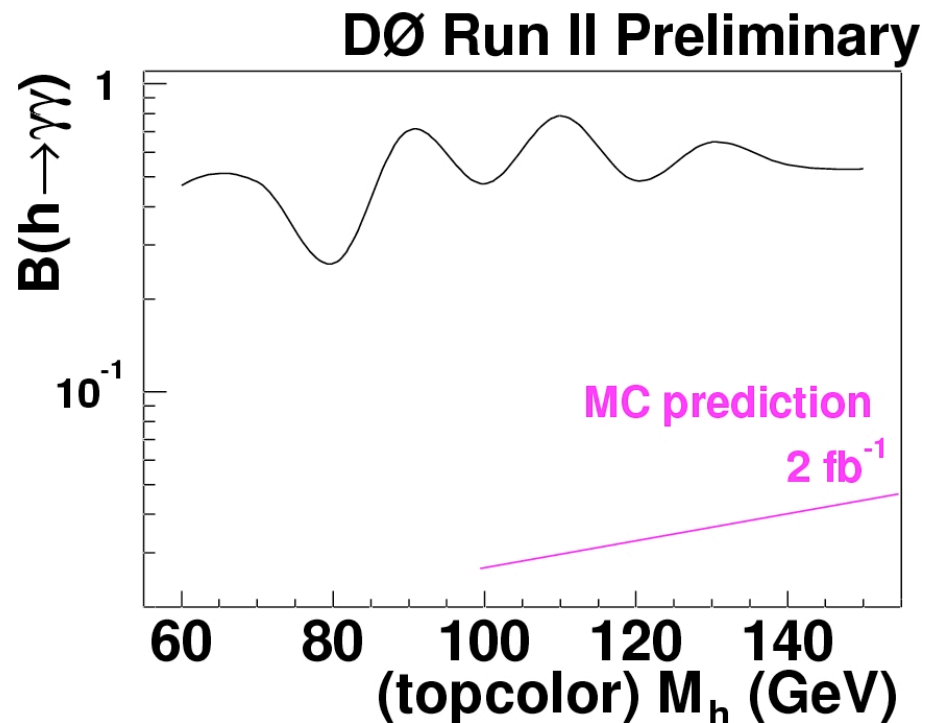
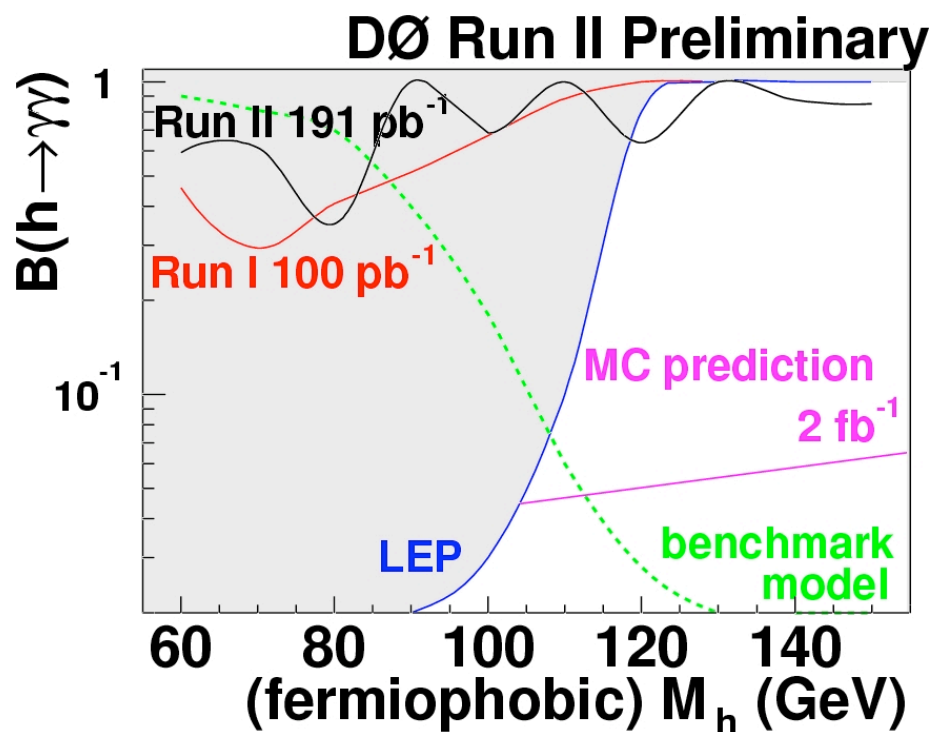
- Some extensions of SM contain Higgs w/ large $B(H \rightarrow \gamma\gamma)$
 - Fermiophobic Higgs : does not couple to fermions
 - Topcolor Higgs : couples to only to top (i.e. no other fermions)
- ♣ Important discovery channel at LHC
- ♣ Event selection
 - 2 Isolated γ 's with
 - $p_T > 25 \text{ GeV}$
 - $|\eta| < 1.05$ (CC) or $1.5 < |\eta| < 2.4$ (EC)
 - $p_T(\gamma\gamma) > 35 \text{ GeV}$ (optimised)
- BG: mostly jets faking photons
 - Syst. error about 30% per photon!
 - Estimated from Data

$\int \mathcal{L} dt = 191 \text{ pb}^{-1}$



Non-SM Light Higgs $H \rightarrow \gamma\gamma$

Perform counting experiments on optimized sliding mass window to set limit on $B(H \rightarrow \gamma\gamma)$ as function of $M(H)$



$\gamma\gamma+X$: more exclusive channels

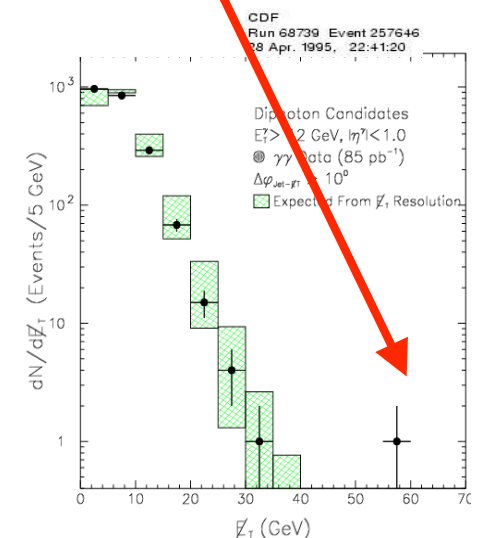
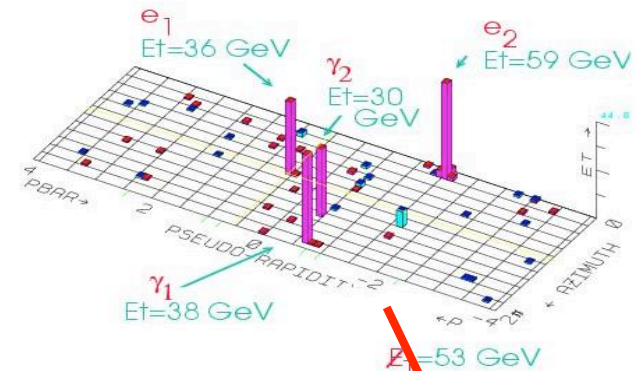
■ Run I:

- found 1 event with 2 photons, 2 electrons and large missing E_T
- SM expectation 10^{-6} (!!!)
- Inspired SUSY model where SUSY is broken at low energies: "Gauge Mediated Symmetry Breaking"

■ Run II:

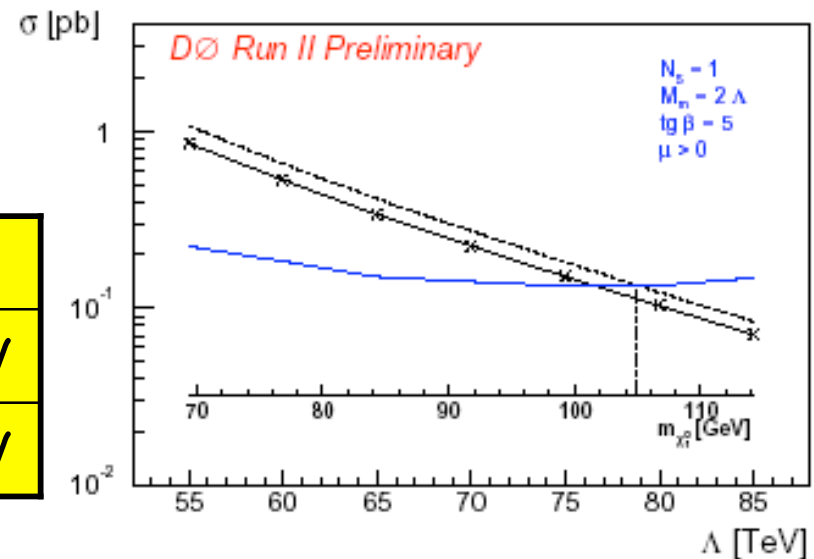
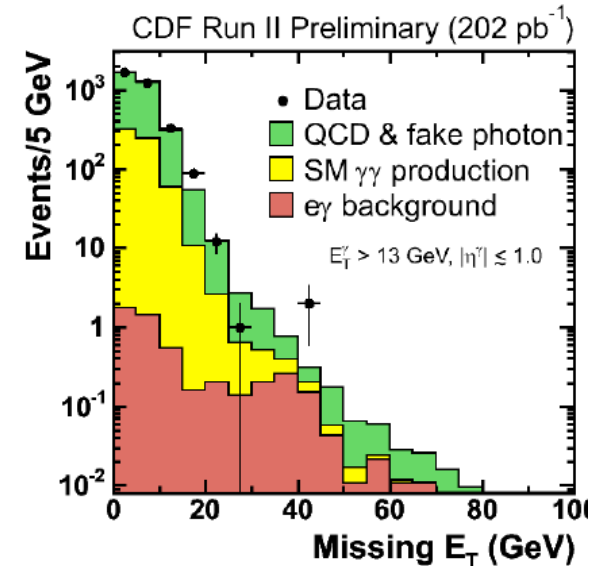
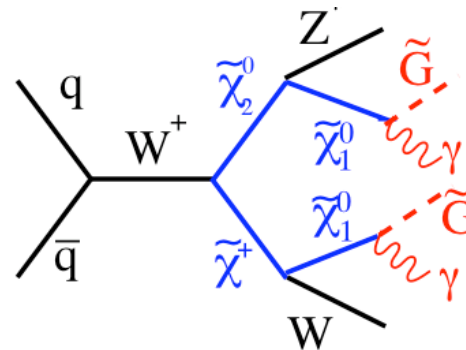
- Any new such event would be exciting!

Event: $2 e + 2 \gamma + \cancel{E}_T$



GMSB: $\gamma\gamma + E_{\cancel{T}}$

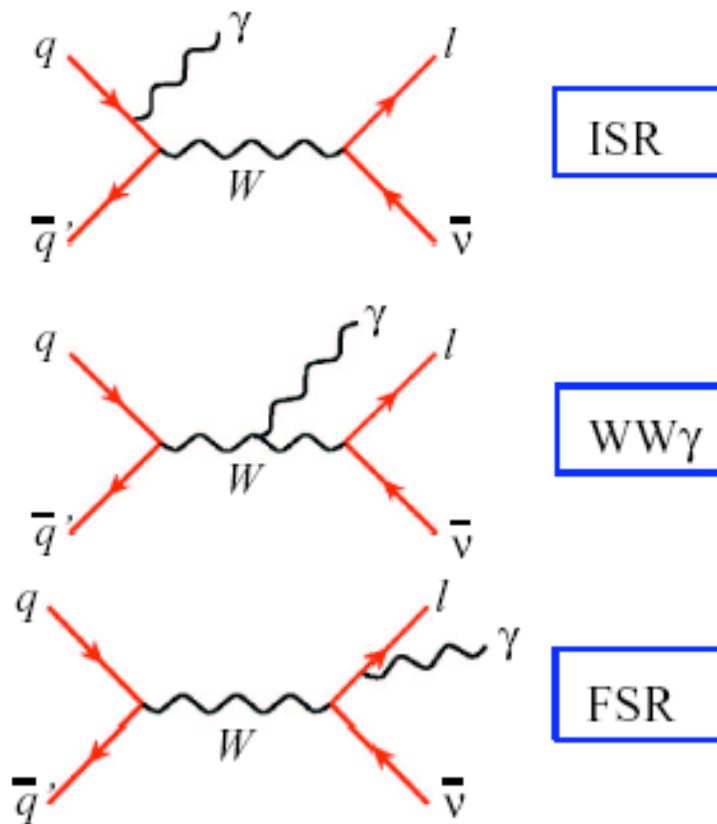
- Assume χ_1^0 is NLSP:
 - Decay to $\tilde{G} + \gamma$
 - \tilde{G} light $M \sim \mathcal{O}(1 \text{ keV})$
 - Inspired by CDF $ee\gamma\gamma + E_{\cancel{T}}$ event
- D0 (CDF) Inclusive search:
 - 2 photons: $E_{\cancel{T}} > 20 \text{ (13) GeV}$
 - $E_{\cancel{T}} > 40 \text{ (45) GeV}$



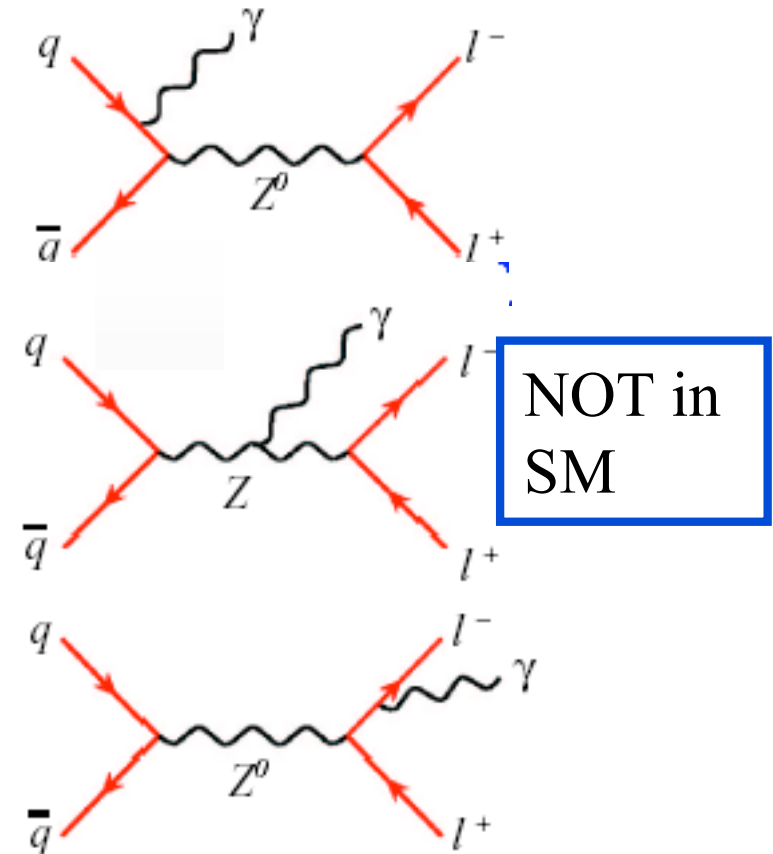
	Exp.	Obs.	$M(\chi_1^+)$
D0	2.5 ± 0.5	1	$> 192 \text{ GeV}$
CDF	0.3 ± 0.1	0	$> 168 \text{ GeV}$

SM Theory of W/Z+ γ Production

Tree-level diagram of
 $\bar{p}p \rightarrow W\gamma \rightarrow l\nu\gamma$

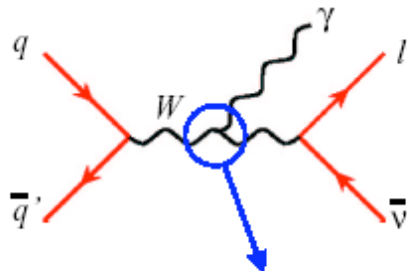


Tree-level diagram of
 $\bar{p}p \rightarrow Z\gamma \rightarrow ll\gamma$



These diagrams interfere and decay products are detected in the detector

Anomalous Couplings

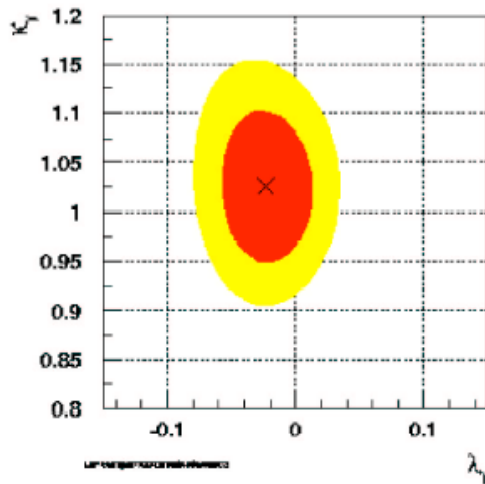
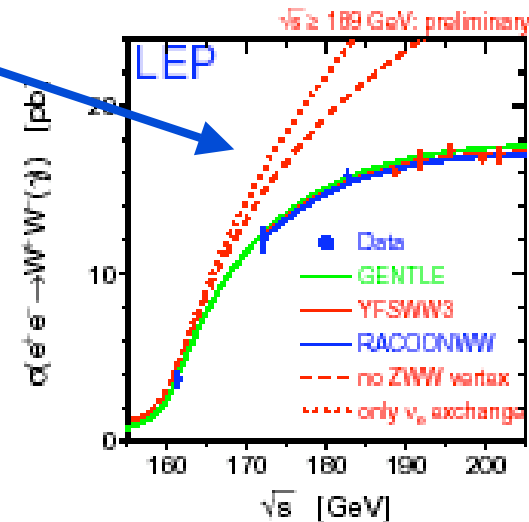


Anomalous couplings : $\Delta\kappa, \lambda$

$$\mu_W = e(1 + \kappa_Y + \lambda_Y)/2m_W$$

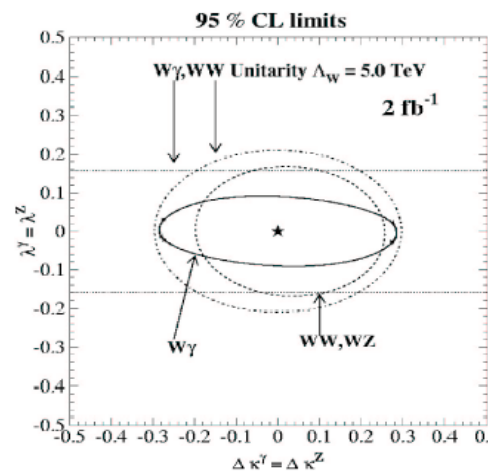
$$q_W = -e(\kappa_Y - \lambda_Y)/m_W^2$$

Existence of $WW\gamma$ vertex indirectly seen at LEP



LEP Preliminary

■ 95% c.l.
■ 68% c.l.
× 2d fit result



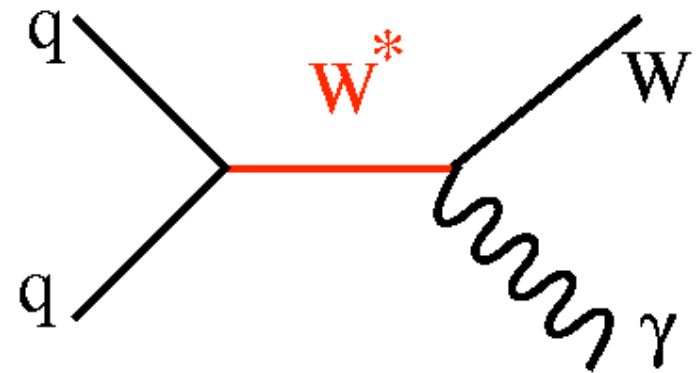
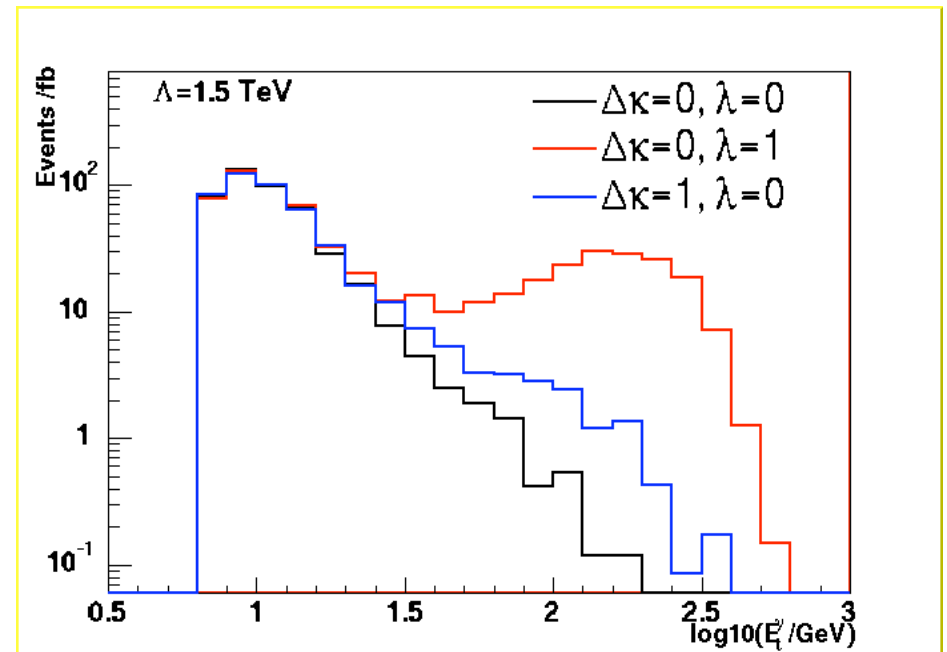
LEP results hard to beat but complementary:

✓ higher energy

✓ $WW\gamma$ vs WWZ

W_γ, Z_γ : beyond the Standard Model

- Any anomalous couplings:
 - Increase in cross-section
 - Excess of events in high E_+^γ region
- Physics beyond SM (e.g. excited W/Z , excited e):
 - Increase in cross-section
 - Excess of events in high E_+^γ region
 - Excess of events in high 3 body Mass region



W+ γ Results

	Electron	Muon
W+ γ MC	126.8 ± 5.8	95.2 ± 4.9
W+jet BG	59.5 ± 18.1	27.6 ± 7.5
W+ γ (tau)	1.5 ± 0.2	2.3 ± 0.2
Z+ γ	6.3 ± 0.3	17.4 ± 1.0
Total SM	194.1 ± 19.1	142.4 ± 9.5
data	195	128
σ^*BR	$19.4 \pm 2.1 \pm 2.9$	$16.3 \pm 2.3 \pm 1.8$

Combined: $\sigma^*BR = 18.1 \pm 1.6(\text{stat}) \pm 2.4(\text{sys}) \pm 1.2(\text{lumi}) \text{ pb}$

SM: $19.3 \pm 1.4 \text{ pb}$

$Z\gamma$ Results

	Electron (\pm sys)	Muon (\pm sys)
Z+ γ MC	30.9 ± 1.6	33.2 ± 1.5
Z+jet BG	2.8 ± 0.9	2.1 ± 0.7
Total SM	33.7 ± 1.8	35.3 ± 1.6
data	35	35
σ^*BR	$4.7 \pm 0.8 \pm 0.3$	$4.5 \pm 0.8 \pm 0.2$

Combined: $\sigma^*BR=4.6 \pm 0.5(\text{stat}) \pm 0.2(\text{sys}) \pm 0.3(\text{lumi})$ pb

SM: 4.5 ± 0.3 pb

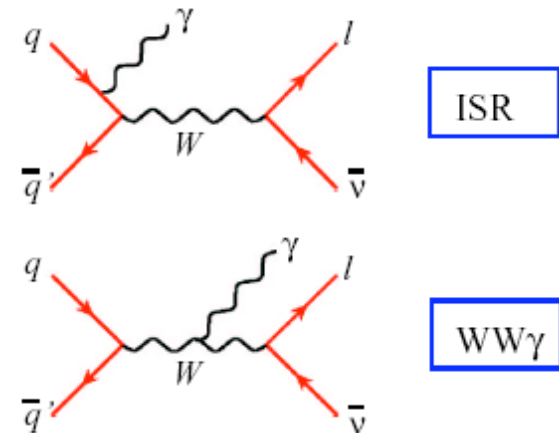
Ratio of Cross Sections

- Inclusive W and Z production:
 - Recent CDF result (hep-ex/0406078)
 - $\sigma(Z) \times \text{BR}(Z \rightarrow ll) / \sigma(W) \times \text{BR}(W \rightarrow lv) = 10.15 \pm 0.21\%$
- Wg and Zg Production for $E_T > 7 \text{ GeV}$:
 - $\sigma(Z\gamma) \times \text{BR}(Z \rightarrow ll) / \sigma(W\gamma) \times \text{BR}(W \rightarrow lv) = 4.6/18.1 \approx 25 \pm 5 \%$

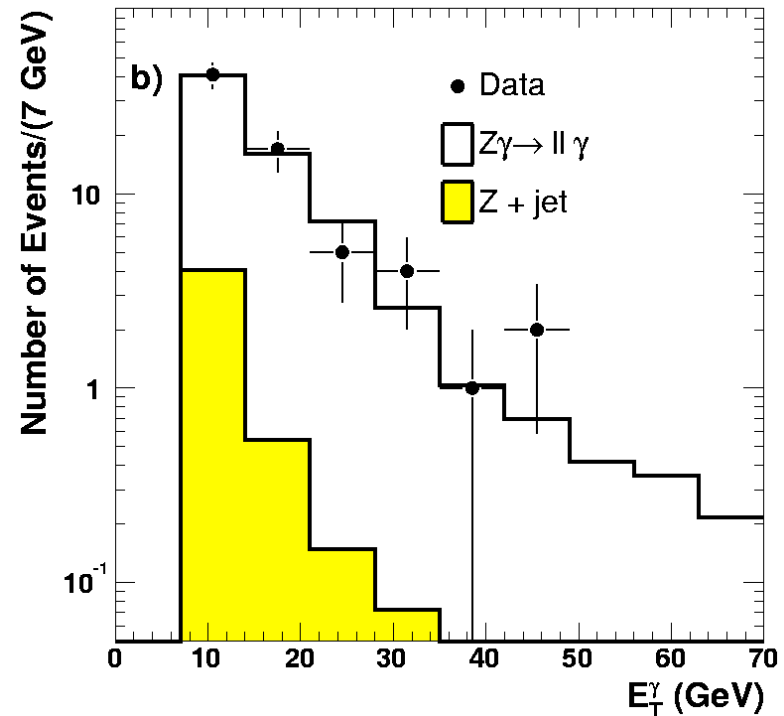
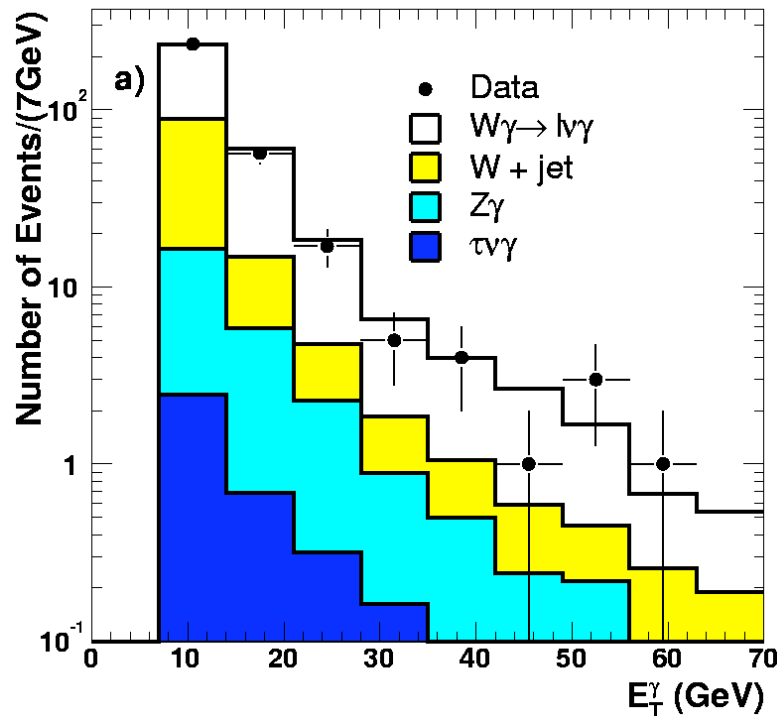
=> Expected due to

- ♣ interference of t-, u-, and s-channel diagrams in $W\gamma$
- ♣ No s-channel diagram in $Z\gamma$ => no interference
- ♣ FSR diagram (1 vs 2 leptons)

=> Indirect Evidence for $WW\gamma$ vertex!

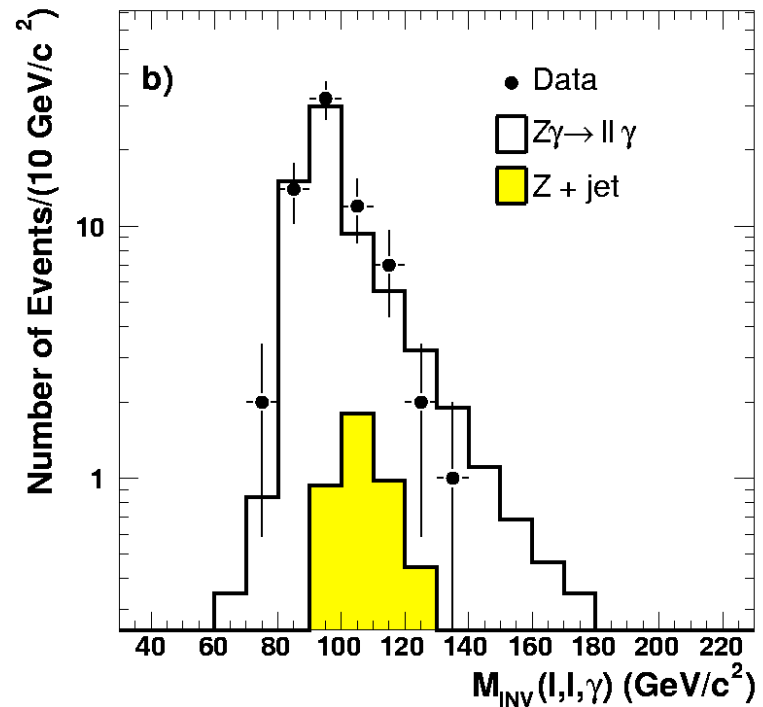
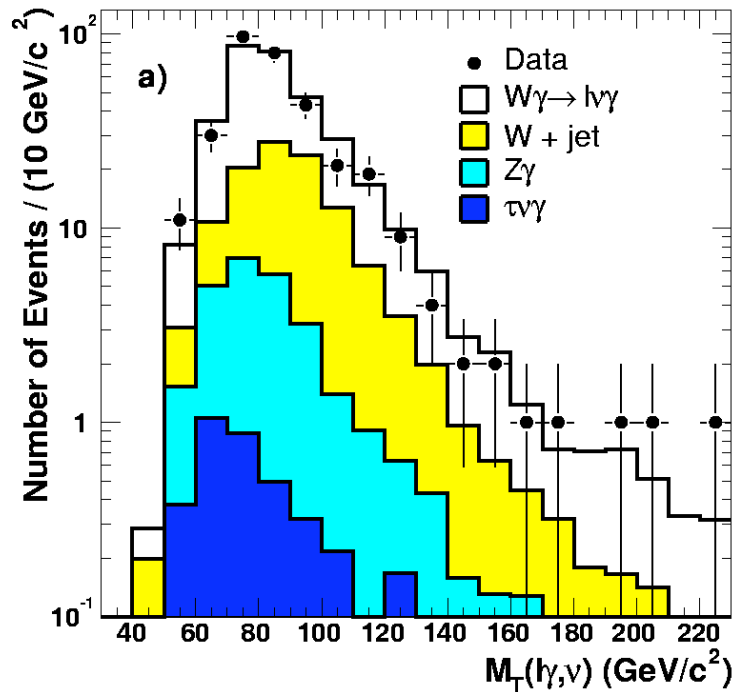


Photon E_T



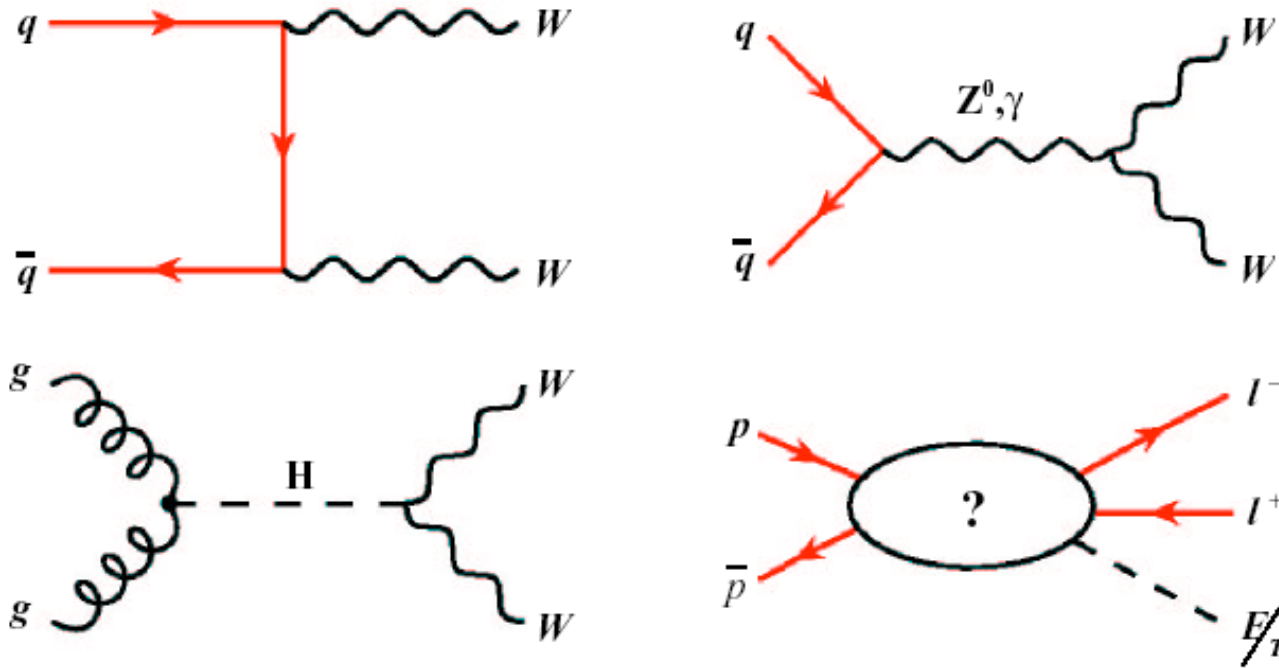
- Data agree well with SM
- Will be used to extract WW_γ and ZZ_γ couplings

Mass



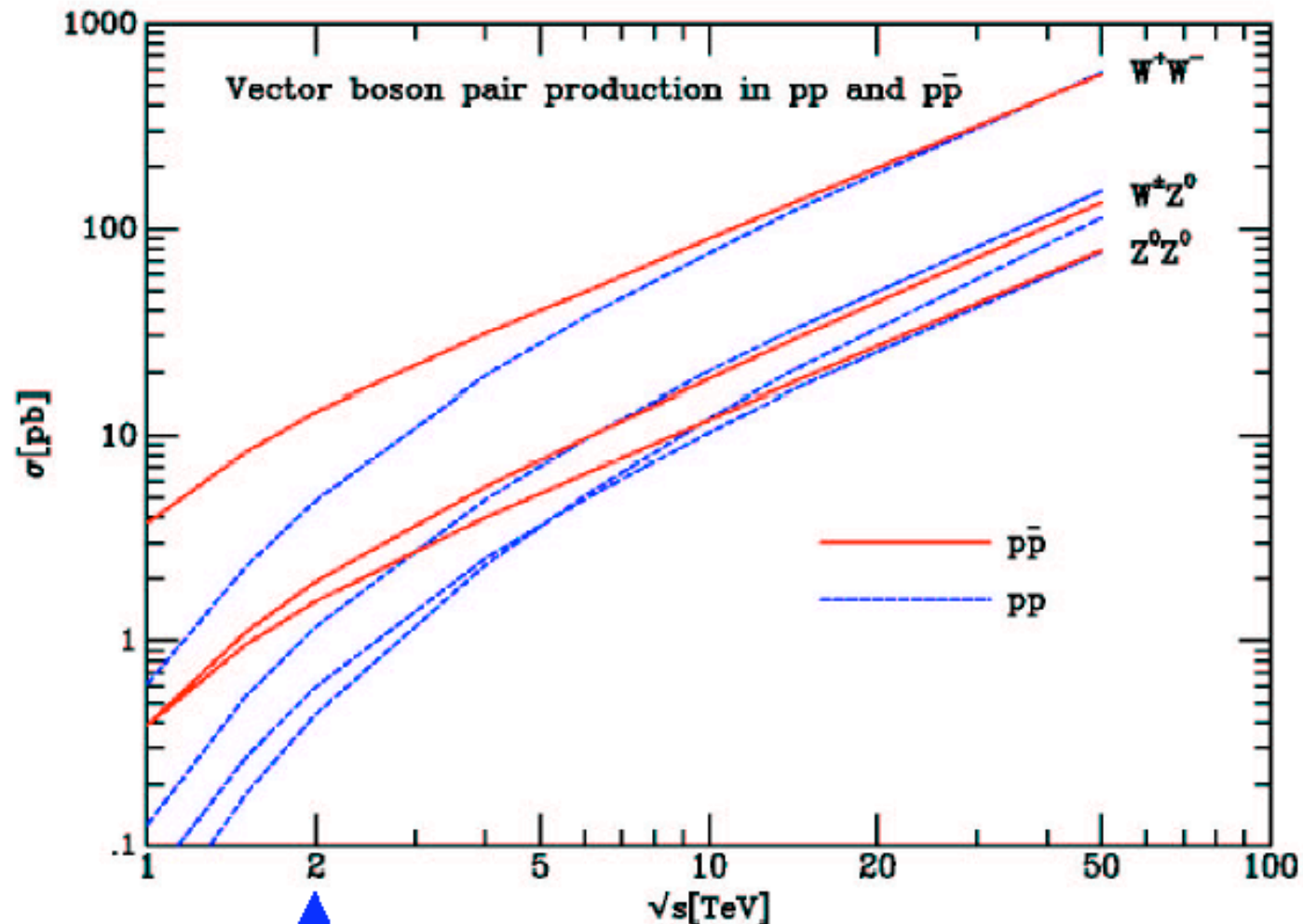
- Data agree well with prediction: no sign of any signal of high mass
- Can be used to constrain e.g. W^* and Z^*

WW: Why?



- Never observed at hadron colliders with any significance (run 1: 5 observed / 1.2 ± 0.3 BG)
- SM test
- Higgs $\rightarrow WW$

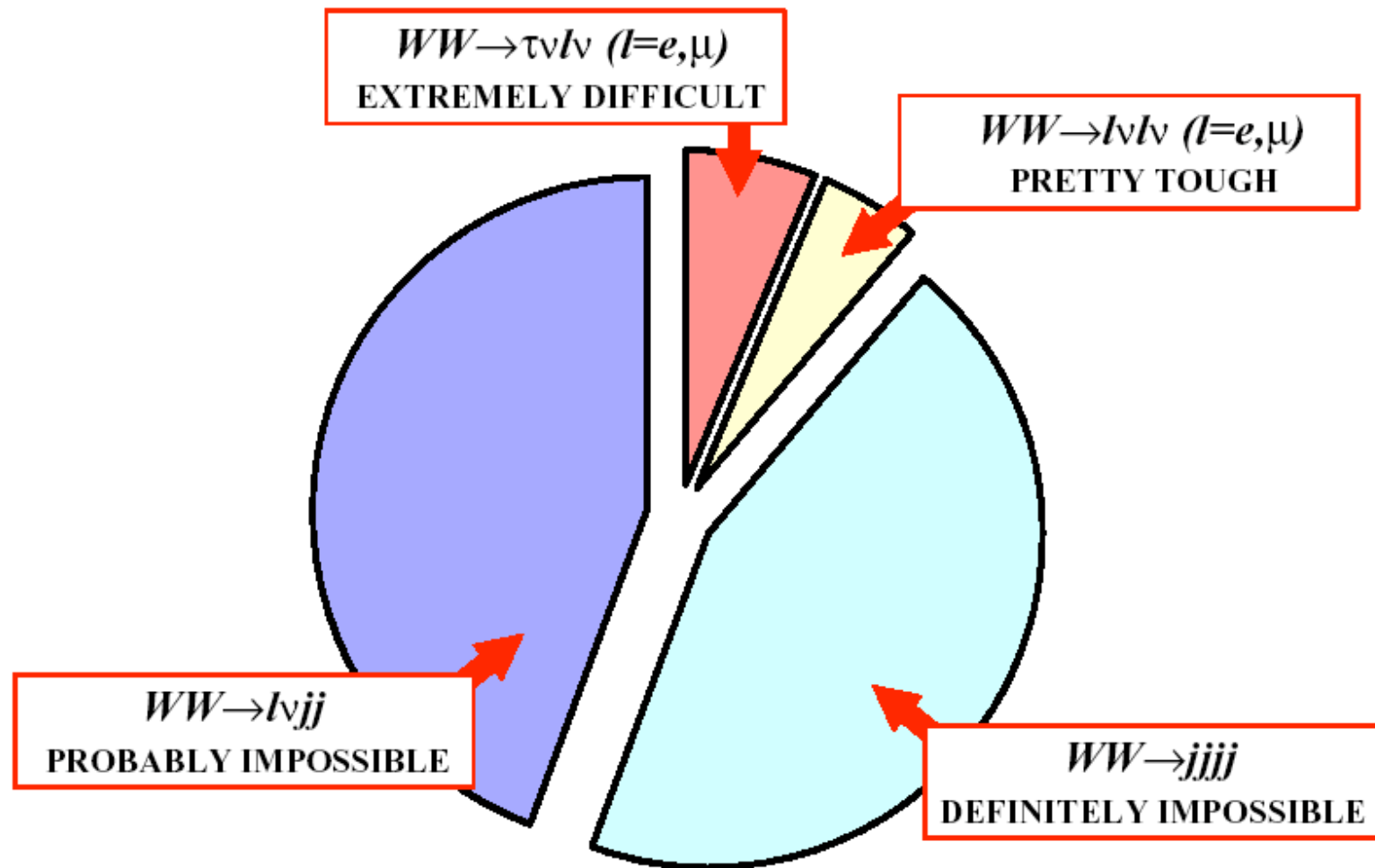
WW Cross Section



Campbell &
Ellis 1999

Tevatron (NLO) : $12.5 \pm 0.8 \text{ pb}$

WW: Decay Channels

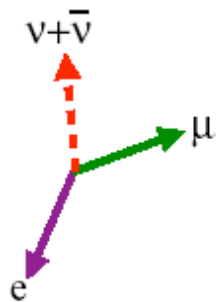


WW: Cross Section Results

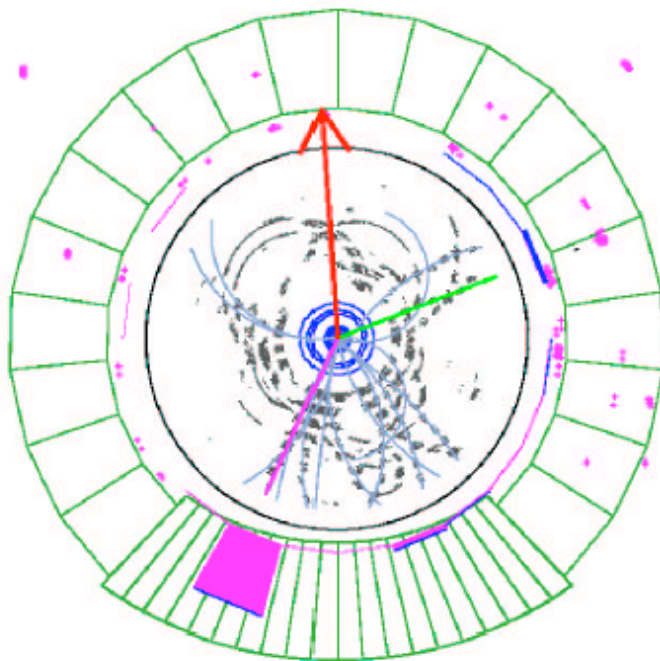
	DILEPTON	LEPTON+TRACK
WW Signal	11.3 ± 1.3	16.3 ± 0.4
Drell-Yan Background	1.8 ± 0.4	1.8 ± 0.3
Fake Background	1.1 ± 0.5	9.1 ± 0.8
Other Background	1.9 ± 0.2	4.2 ± 0.1
Total Background	4.8 ± 0.7	15.1 ± 0.9
Total Expected	16.1 ± 1.6	31.5 ± 1.0
Data Observed	17	39
$\sigma(\text{WW})$ [pb]	$14.3^{+5.6}_{-4.9} \text{ (stat)} \pm 1.6 \text{ (syst)} \pm 0.9 \text{ (lum)}$	$19.4 \pm 5.1 \text{ (stat)} \pm 3.5 \text{ (syst)} \pm 1.2 \text{ (lum)}$

- 2 independent analysis (high purity vs high acceptance)
=>Consistent results
- First significant signal: significance $> 3\sigma$
- Agree with theor. prediction: $\sigma_{\text{NLO}} = 12.5 \pm 0.8 \text{ pb}$

WW Candidate Event



- $e\mu$ channel has little Standard Model background
- Signal/Background ≈ 4

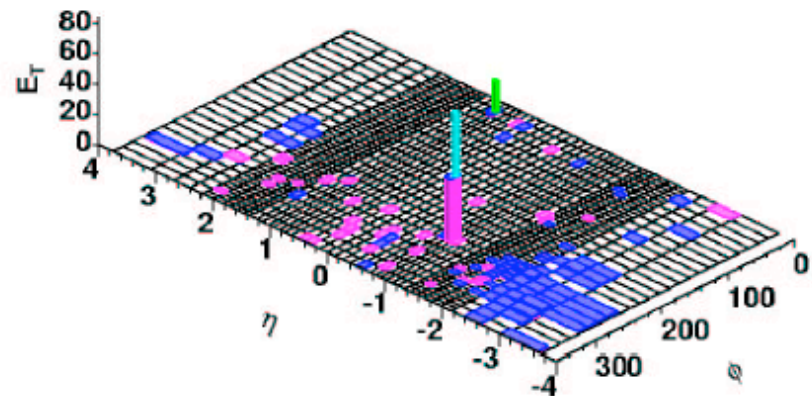


Run 155364 Event 3494901 : $WW \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu$ Candidate

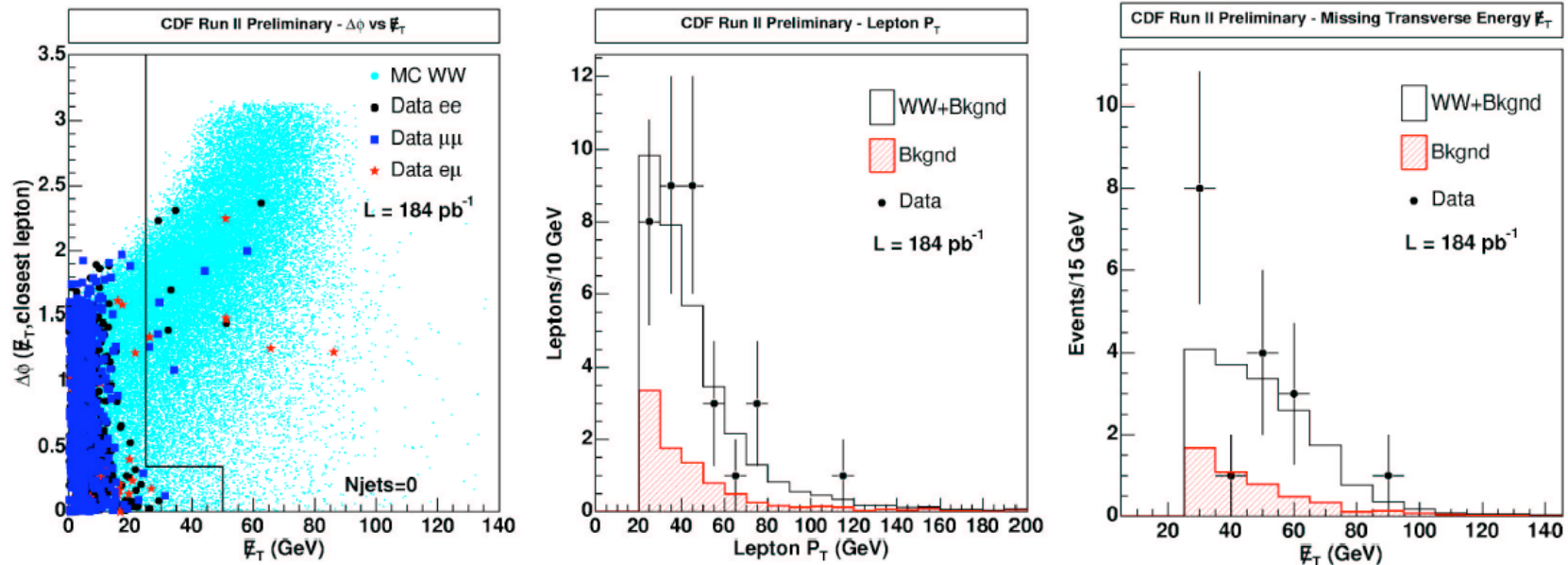
$p_T(e) = 42.0 \text{ GeV}/c$; $p_T(\mu) = 20.0 \text{ GeV}/c$; $M_{e\mu} = 81.5 \text{ GeV}$

$\cancel{E}_T = 64.8 \text{ GeV}$; $\Phi(\cancel{E}_T) = 1.6$

$\Delta\Phi(\cancel{E}_T, \text{lepton}) = 1.3$; $\Delta\Phi(e, \mu) = 2.4$; Opening-Angle(e, μ) = 2.6



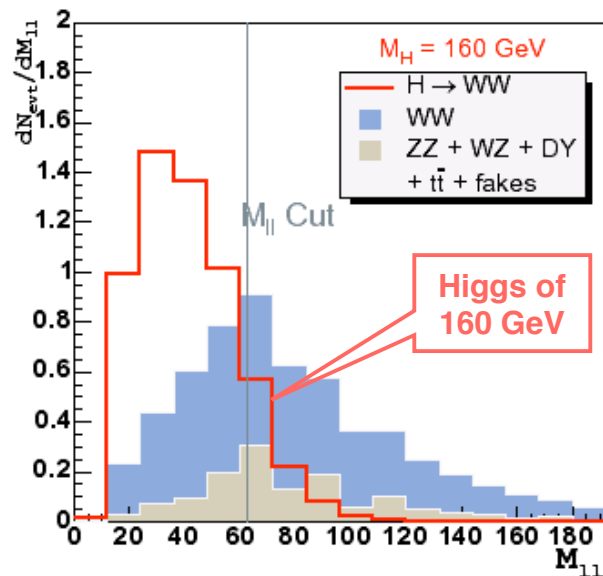
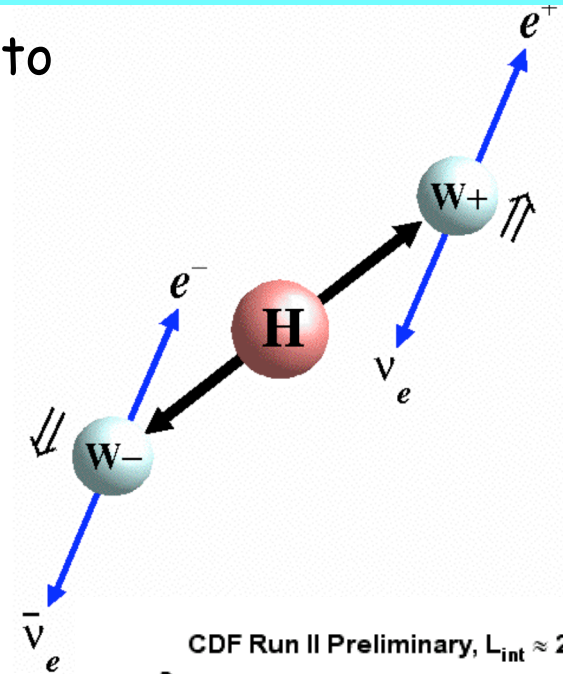
WW kinematic distributions



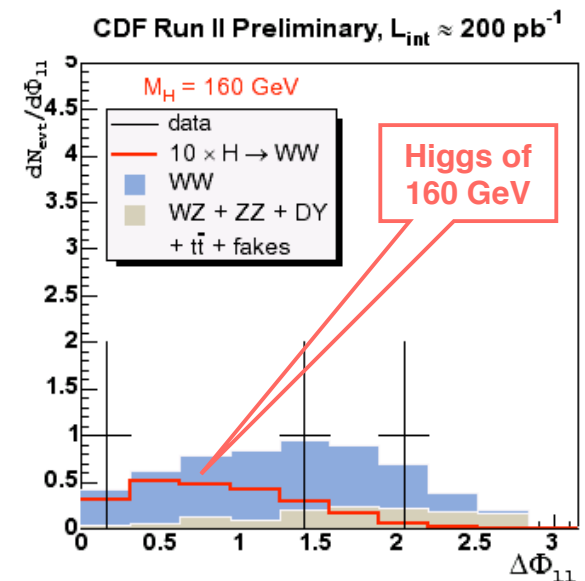
- Kinematic properties as expected from SM WW production
- \Rightarrow use the data to constrain new physics

$$H \rightarrow WW(*) \rightarrow l^+ l^- \nu \nu$$

- Higgs mass reconstruction not possible due to two neutrinos:
 - Dilepton mass lower for $h \rightarrow WW$: mass dependent cut
- Employ spin correlations to suppress WW background:
 - leptons from $h \rightarrow WW(*) \rightarrow l^+ l^- \nu \nu$ tend to be collinear



M_H	Cut
140 GeV	$M_{ll} \leq 55.0 \text{ GeV}$
150 GeV	$M_{ll} \leq 57.5 \text{ GeV}$
160 GeV	$M_{ll} \leq 62.5 \text{ GeV}$
170 GeV	$M_{ll} \leq 70.0 \text{ GeV}$
180 GeV	$M_{ll} \leq 80.0 \text{ GeV}$

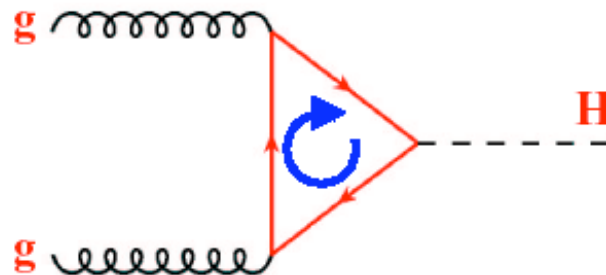


$$H \rightarrow WW^{(*)} \rightarrow l^+ l^- \nu \nu$$

- Similar analysis by D0

D0	ee	eμ	μμ
Observed	2	2	5
Expected	2.7 ± 0.4	3.1 ± 0.3	5.3 ± 0.6

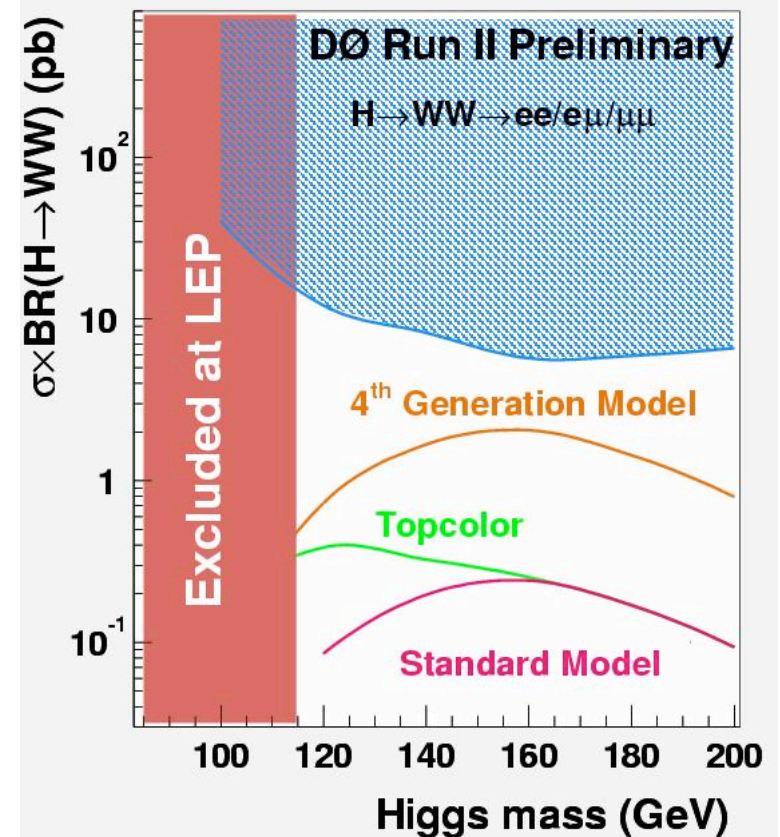
- Neither CDF nor D0 see any evidence for h production => set upper limit on cross section



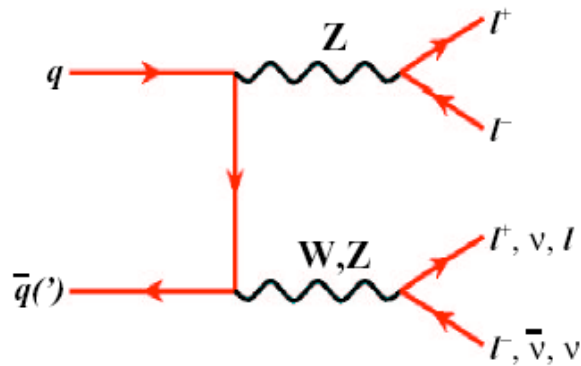
$$\sigma(gg \rightarrow H; 4G) \sim 9 \times \sigma(gg \rightarrow H; 3G)$$

- Expect 0.11 events for 160 GeV SM Higgs with 200/pb

Excluded cross section times Branching Ratio at 95% C.L.



WZ and ZZ



Select 2 leptons with $M(l\bar{l})$ in Z mass range and

- 2 leptons (ZZ- $\rightarrow l\bar{l}l\bar{l}$)
- 1 lepton and \cancel{E}_t (WZ- $\rightarrow l\bar{l}\nu$)
- Significant \cancel{E}_t (ZZ- $\rightarrow l\bar{l}\nu\nu$)

CDF Run II Winter 2004 Preliminary, $\mathcal{L}=194 \text{ pb}^{-1}$

Process	$l_1 l_2 l_3 l_4$	$l_1 l_2 l_3 \cancel{E}_T$	$l_1 l_2 \cancel{E}_T$	Combined
ZZ	0.07 ± 0.01	0.13 ± 0.01	0.87 ± 0.14	1.07 ± 0.15
ZW	-	0.81 ± 0.07	0.86 ± 0.14	1.67 ± 0.19
ZZ+ZW	0.07 ± 0.01	0.94 ± 0.08	1.73 ± 0.27	2.72 ± 0.33
WW	-	-	1.26 ± 0.20	1.26 ± 0.20
Fake	0.01 ± 0.02	0.07 ± 0.06	0.56 ± 0.30	0.64 ± 0.34
Drell-Yan	-	-	0.31 ± 0.13	0.31 ± 0.13
$t\bar{t}$	-	-	0.08 ± 0.02	0.08 ± 0.02
Total Background	0.01 ± 0.02	0.07 ± 0.06	2.21 ± 0.38	2.29 ± 0.42
Expected S. + B.	0.08 ± 0.02	1.01 ± 0.10	3.94 ± 0.57	5.01 ± 0.64
Data	0	0	4	4

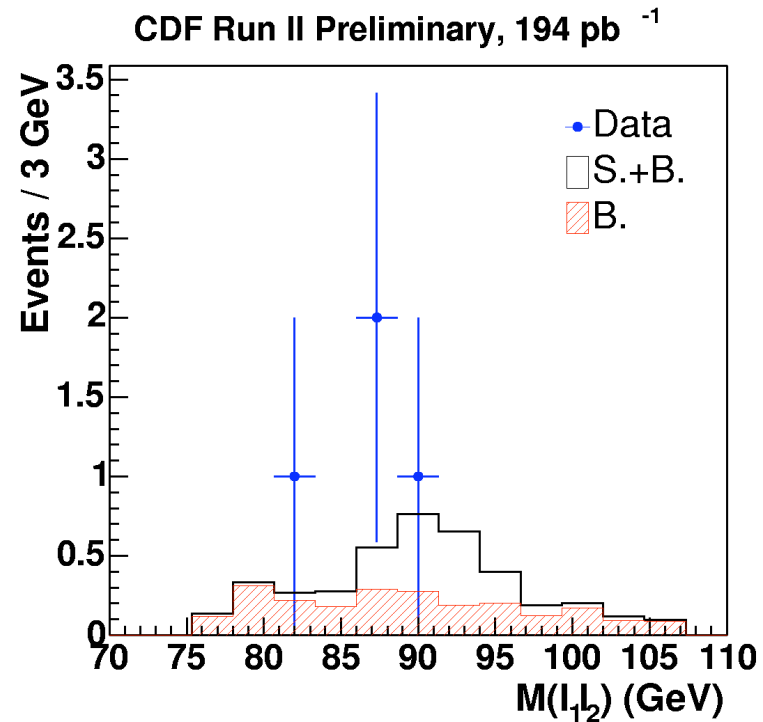
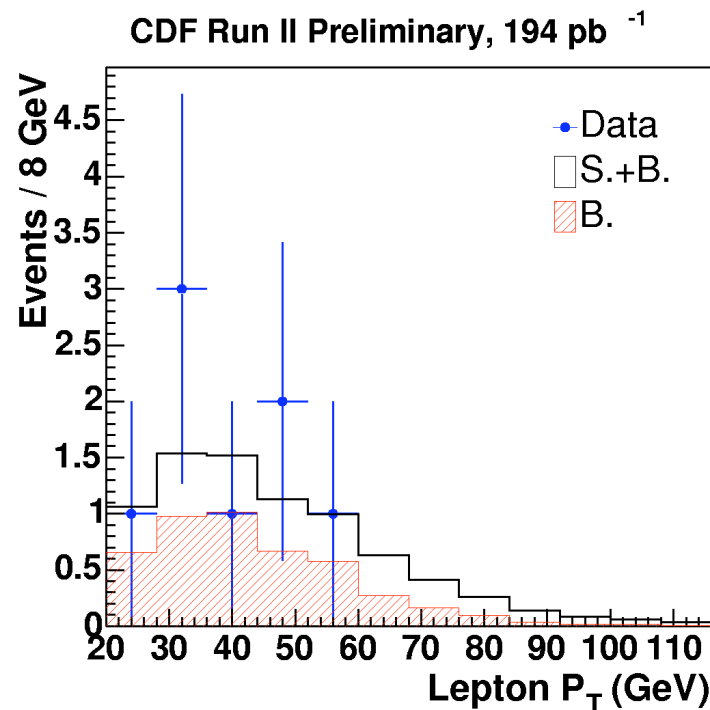
Expect 5.0 ± 0.6 events

Observe 4 events \Rightarrow

$\sigma < 13.9 \text{ pb @ 95\% C.L.}$

NLO: $\sigma = 5.2 \pm 0.4 \text{ pb}$

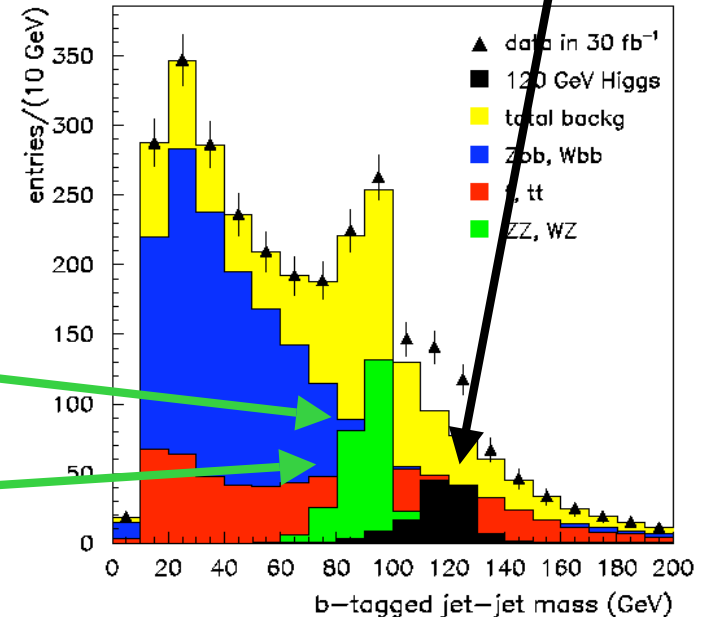
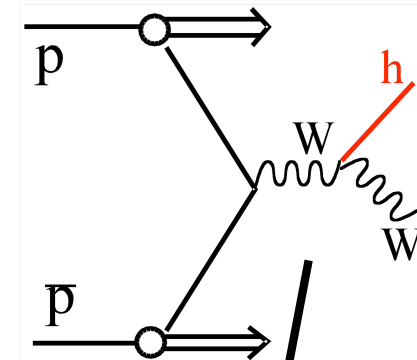
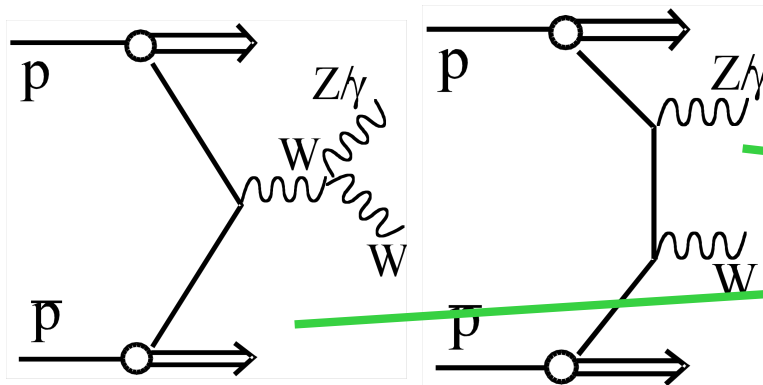
WZ/ZZ: kinematics



- Consistent with expectation
- More data needed!

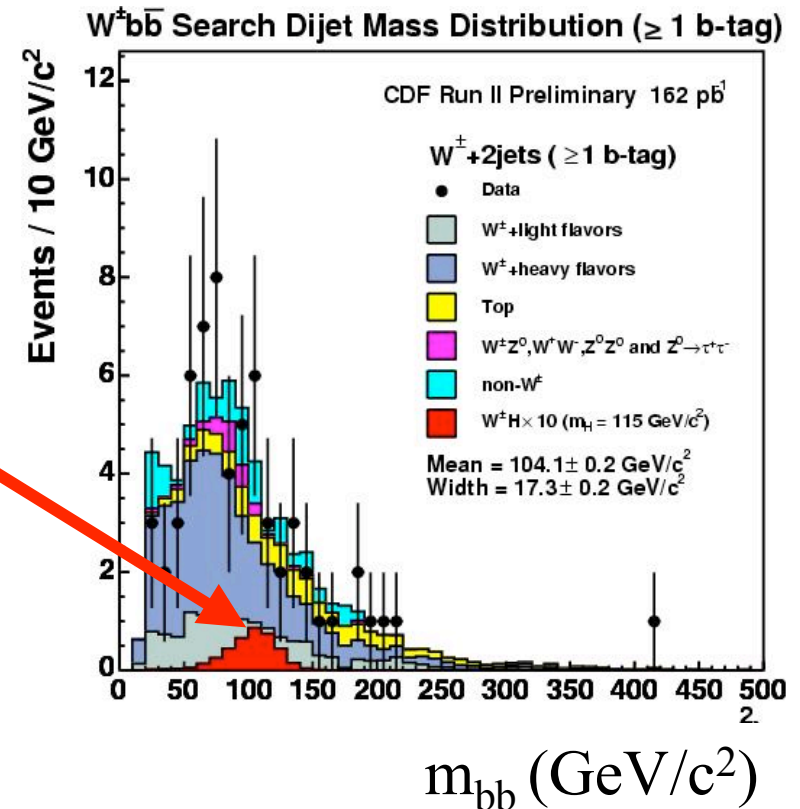
WZ/ZZ and Wh Production

- Large backgrounds from QCD processes: W +jets, Z +jets
- Use $h \rightarrow b\bar{b}$ channel for Higgs search
- $WZ \rightarrow Wbb$ will be observable before seeing the higgs \Rightarrow excellent calibration channel
- Exercises mass resolution: combining calorimeter and tracking \Rightarrow 30% improvement in energy resolution

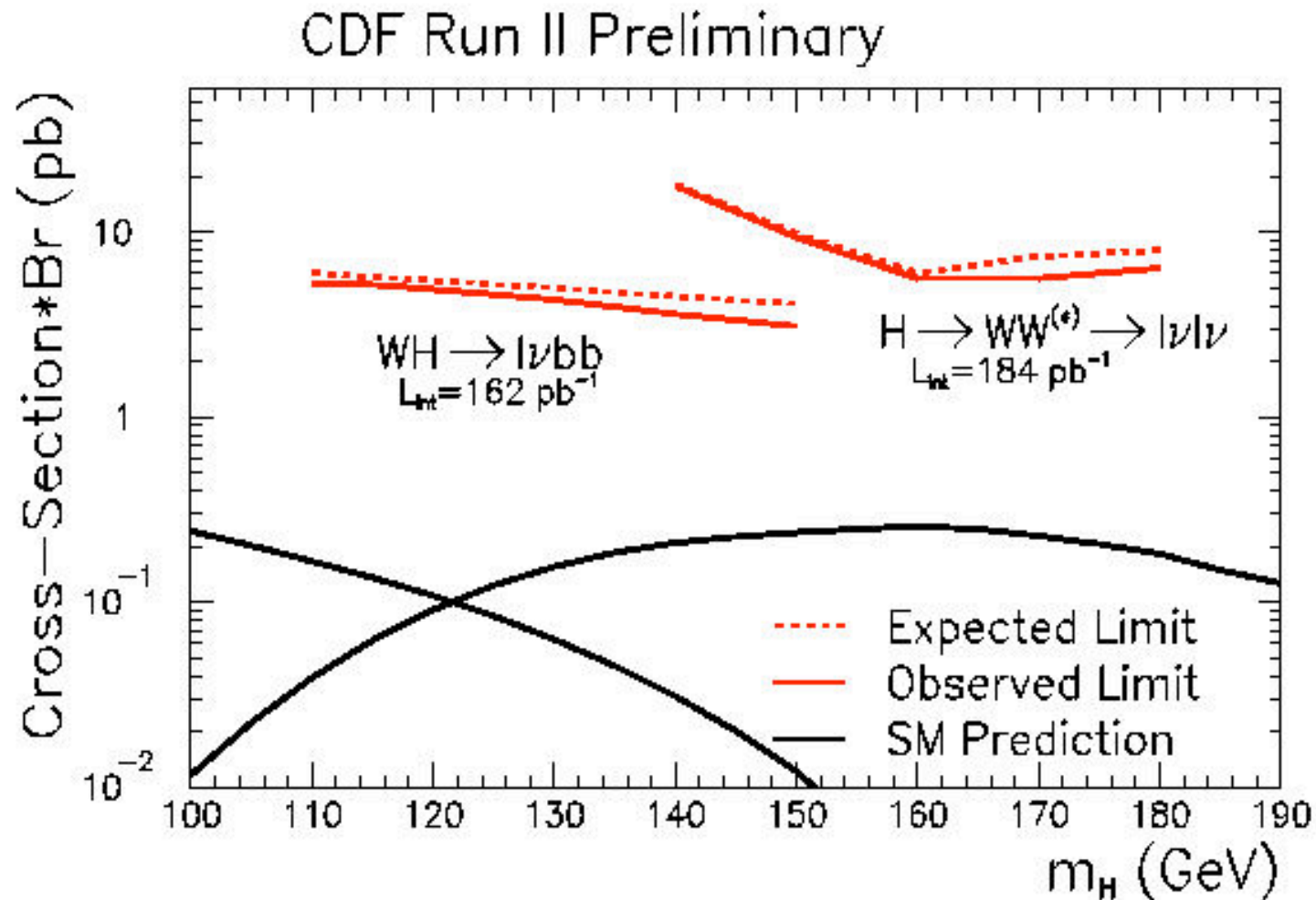


Wh Production: Run 2 data

- Selection:
 - $W(\rightarrow \mu\nu \text{ or } e\nu)$
 - 2 jets: 1 b-tagged
- Search for peak in dijet invariant mass distribution
- No evidence yet for WZ or Wh

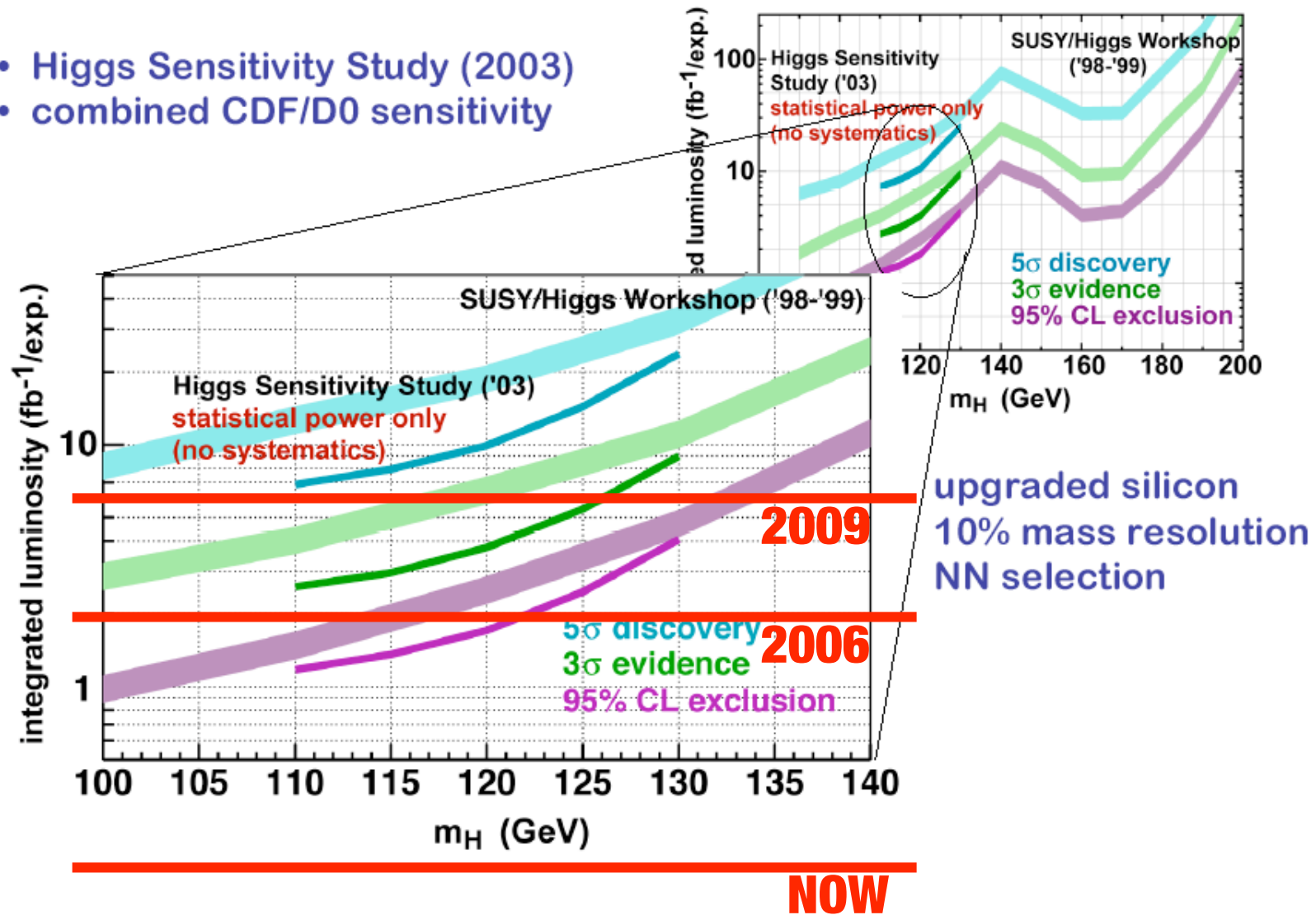


Summary of CDF Higgs Searches

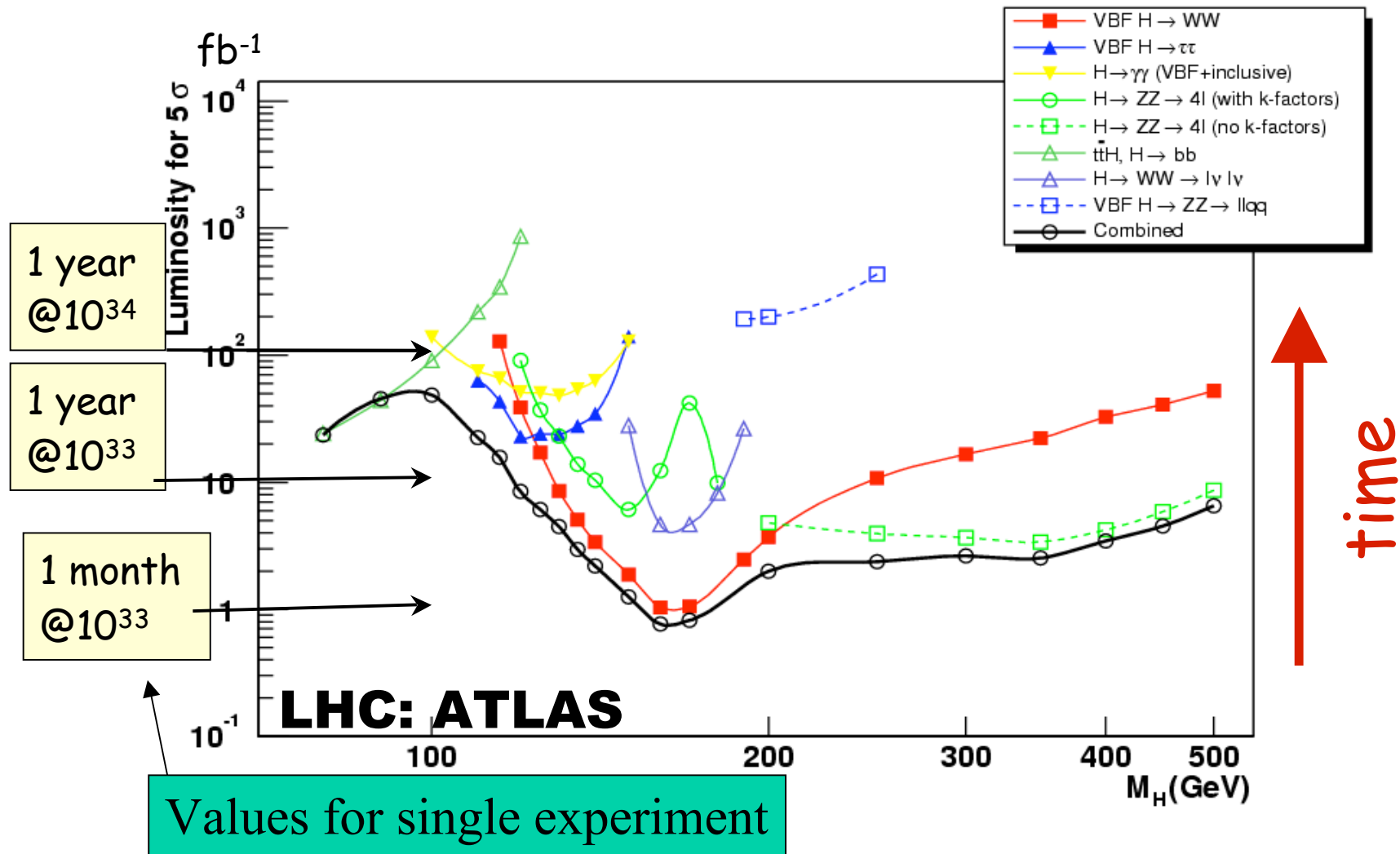


Higgs Discovery at Tevatron?

- Higgs Sensitivity Study (2003)
- combined CDF/D0 sensitivity

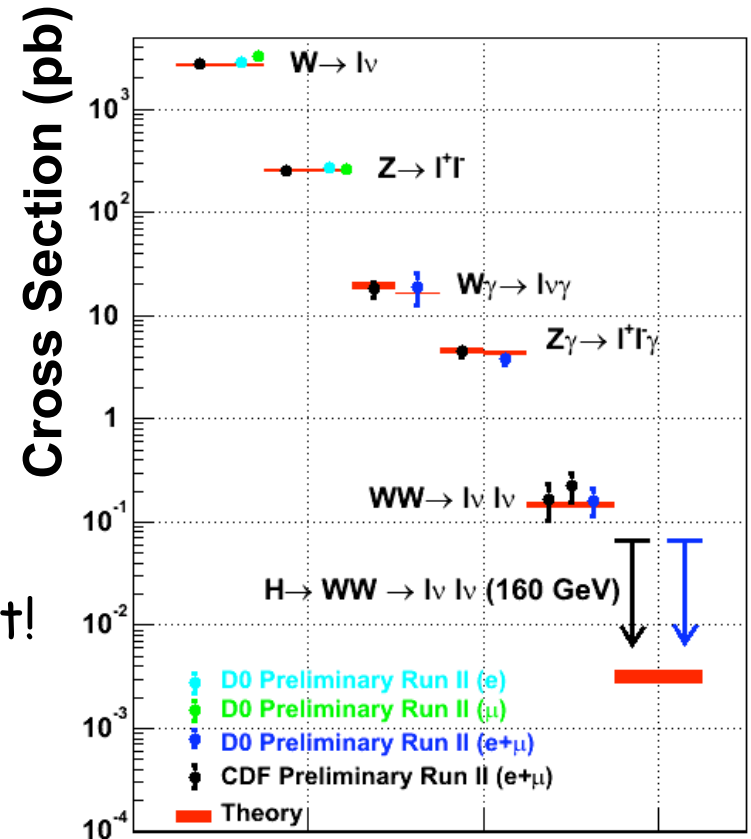


Higgs Discovery at the LHC?



Summary and Outlook

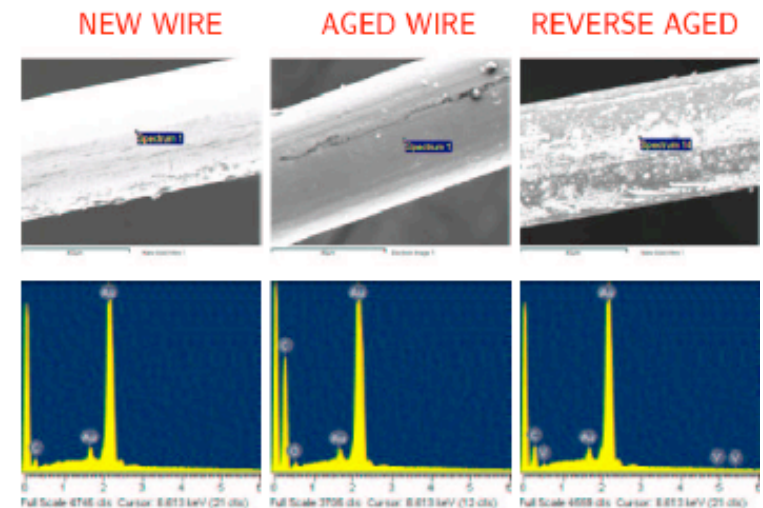
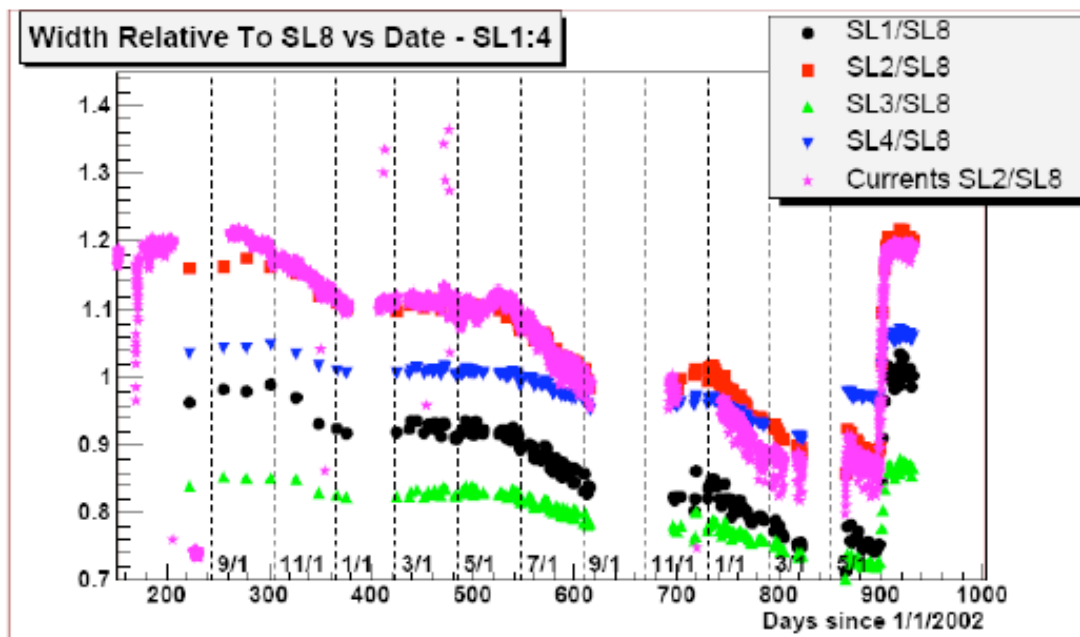
- Diboson Production excellent probe for New Physics
 - Higgs production
 - SUSY
 - Large Extra Dimensions
 - Precision test of $SU(2) \times U(1)$ gauge structure
- Many new results from Tevatron
 - Machine and experiments running great!
 - Have got 2x more data on tape!
 - Anticipate $1.5\text{--}2\text{ fb}^{-1}$ by 2007 and $4.4\text{--}8.6\text{ fb}^{-1}$ by 2009
- Crucial for Higgs discovery at both Tevatron and LHC



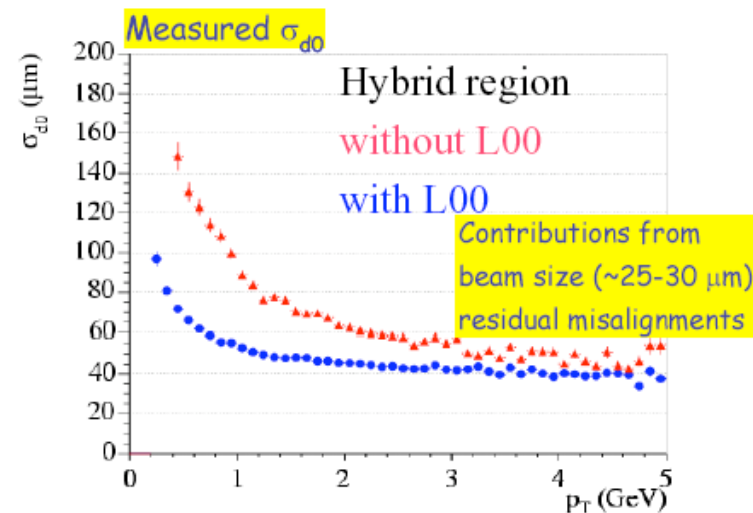
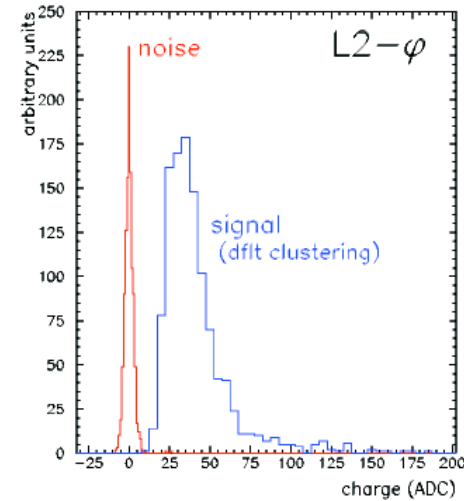
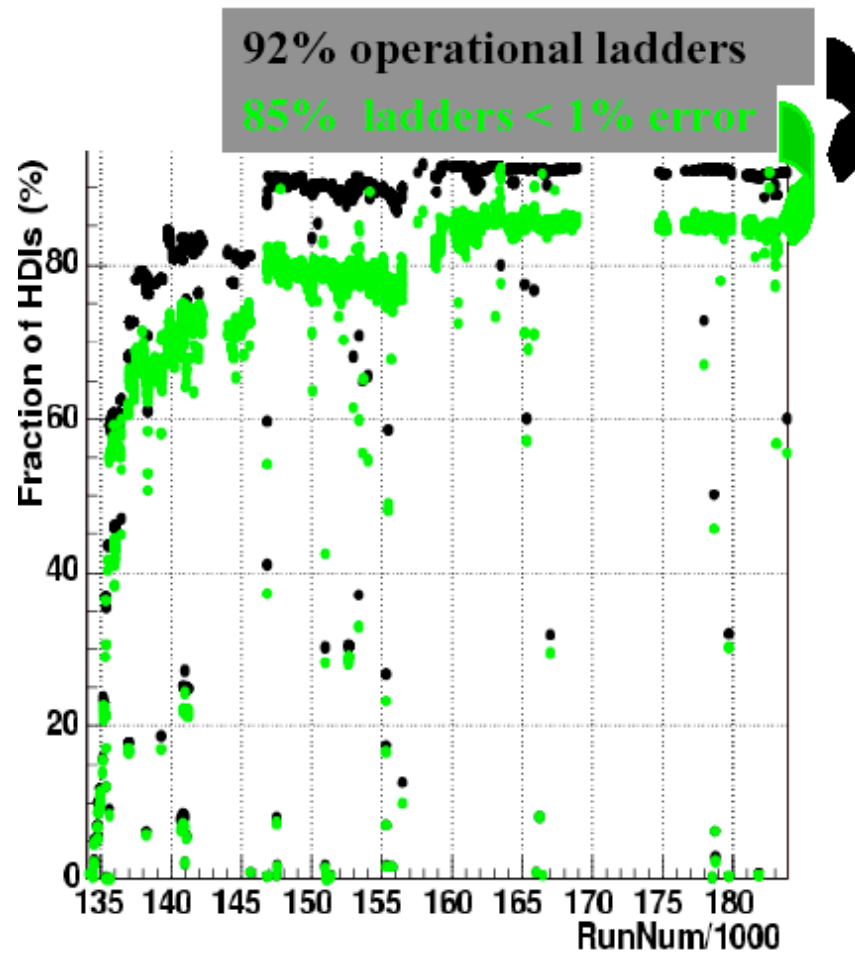
Backup Slides

CDF: COT Aging Problem Solved!

- Gaseous tracking chamber COT: wire aging problem seen in 2003-2004
- hydrocarbon residue detected on sense wires where gain had been falling
- addition of air (probably the oxygen) reverses the aging
- Chamber gains back go pre-aged status
- Voltages reduced on inner superlayers from February to May 2004



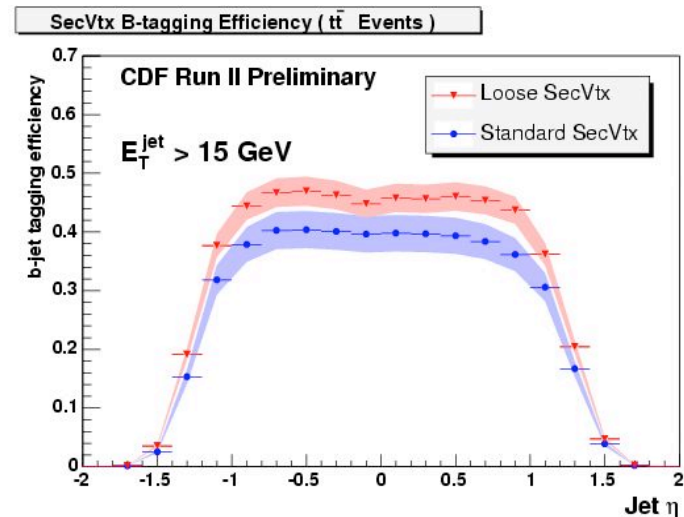
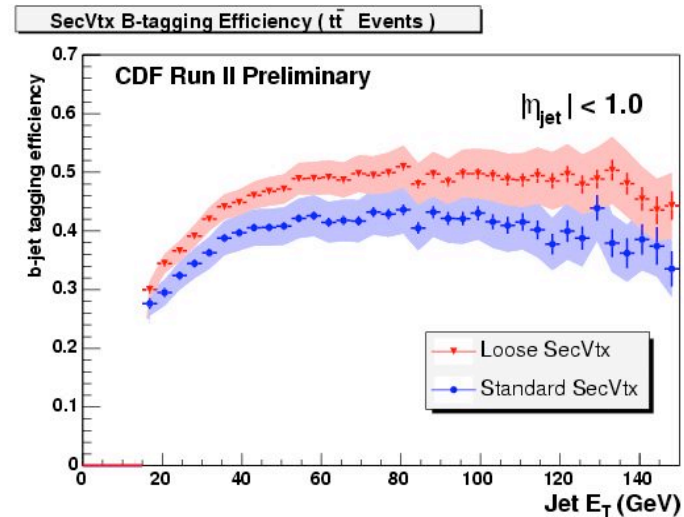
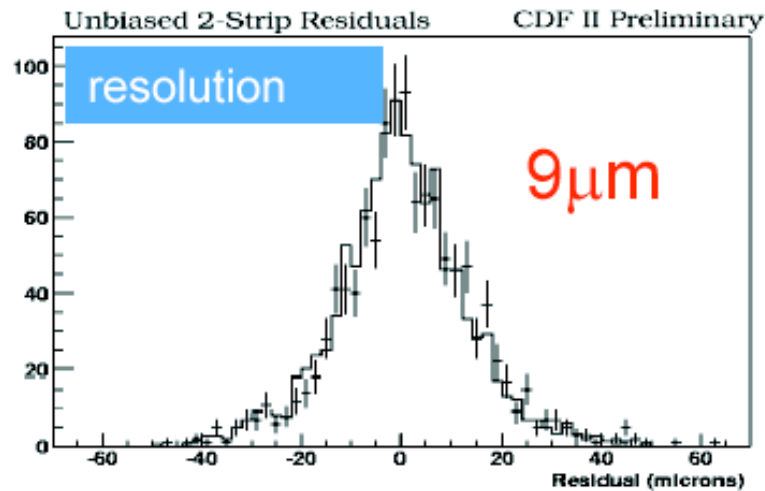
Silicon Performance



See talk by R. Wallny

CDF: B-tagging and tracking

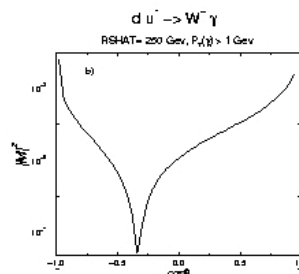
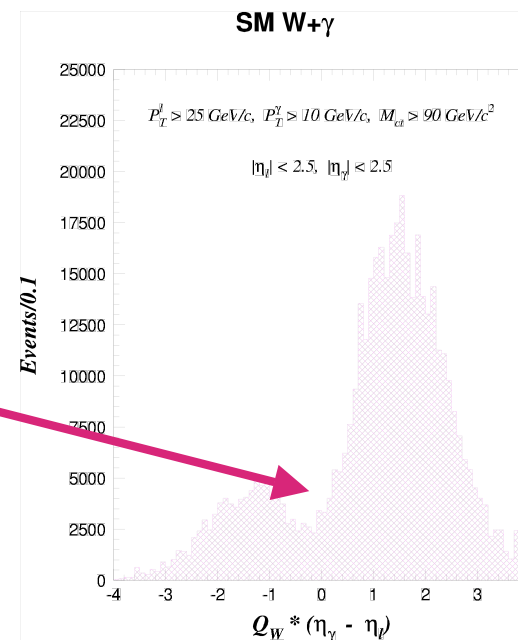
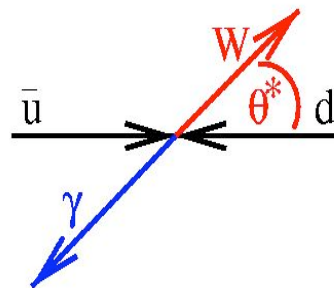
Requirement	Efficiency	Requirement	Efficiency
$N_{r\phi} \geq 3$	94%	$N_z \geq 3$	80%
$N_{r\phi} \geq 4$	90%	$N_z \geq 4$	61%
$N_{r\phi} = 5$	46%	$N_z = 5$	26%



Radiation Zero

- "Radiation Zero" unique to TeVatron:

- suppressed w.g. for W^-
 $\cos_{-}^* = -(1+2Q_i) = -1/3$
- Observable in angular separation of lepton and photon



W + Photon as Search

Run I: $E_t > 25$ GeV, lepton $E_t > 25$ GeV, photon $E_t > 25$ GeV

lepton	Data	SM exp
muon	11	4.2
electron	5	3.4
both	16	7.6

Phys. Rev. Lett. 89, 041802 (2002)

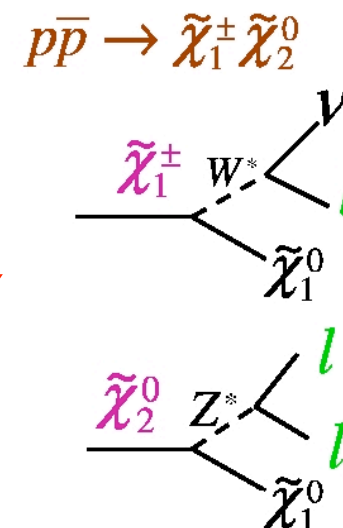
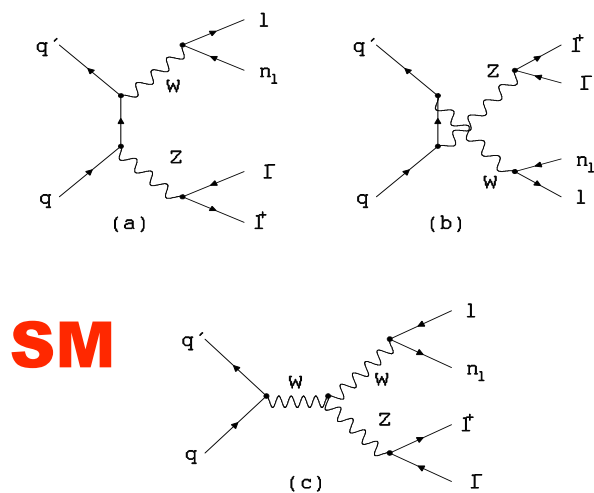
■ Run II:

- Repeat run I analysis (20 x more data)
- Extend to forward region (silicon tracker, new Plug calorimeter, new forward muon system)

WZ Production: leptonic channel

- Leptonic channel ($Z \rightarrow \ell\ell$, $W \rightarrow \ell\nu$) background rather low ($S/B=3$) but cross section also low ($\sigma=2.5$ pb)
- Anomalous couplings: WWZ may be different to $WW\gamma$
- Experimental signature similar to SUSY "trilepton" channel:

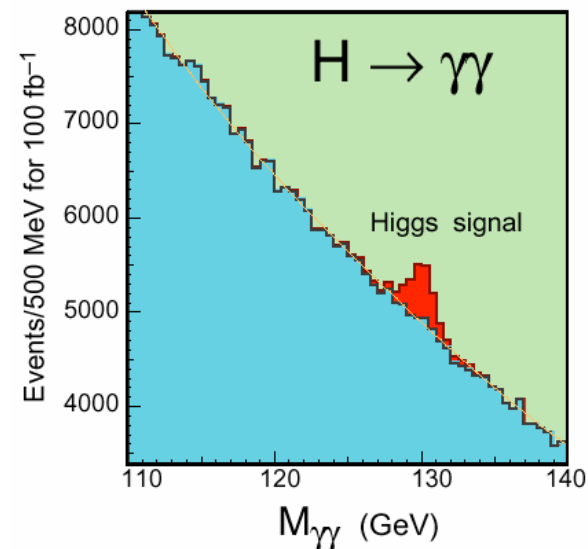
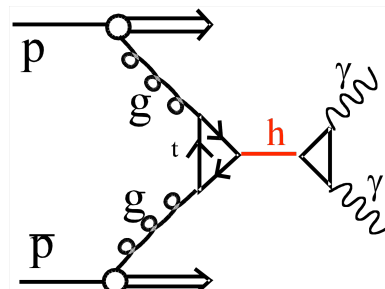
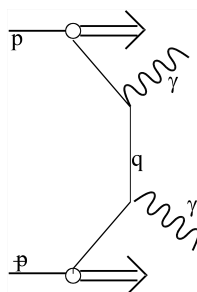
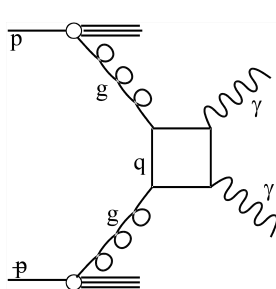
Associated production of chargino and neutralino: disentangle on basis of imbalance in transverse momentum, masses



Di-Boson Production

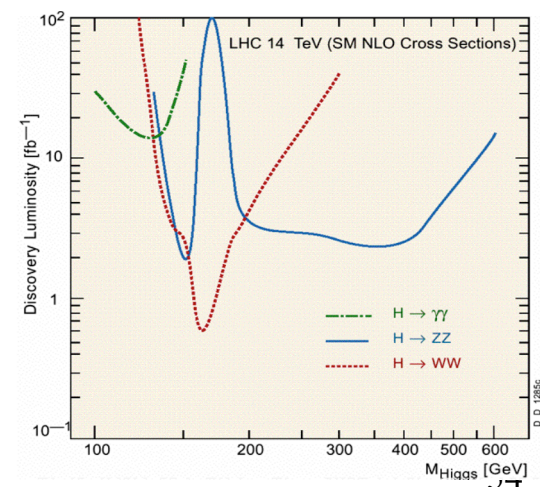
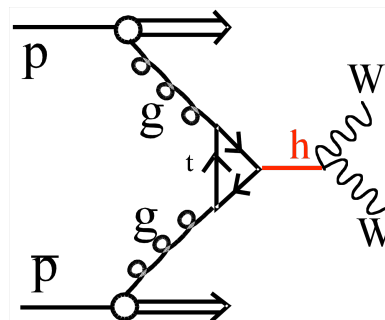
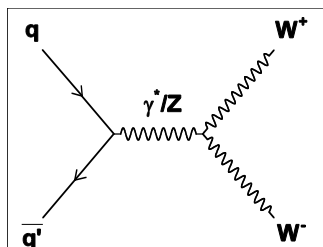
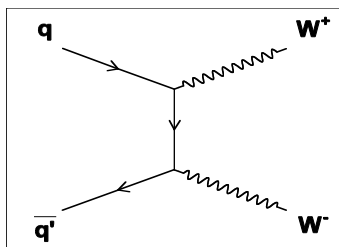
- Di-Photon Production:

discovery channel at LHC for $m_h < 130$ GeV



-WW and ZZ Production:

-discovery channels at LHC for $500 > m_h > 130$ GeV



Why WW scattering?

Without the Higgs, $W_L W_L \rightarrow W_L W_L$ violates perturbative unitarity at 1.2 TeV

($W_T W_T \rightarrow W_T W_T$ doesn't)

In the high energy limit, the W_L ARE the 3 goldstone bosons associated with electroweak symmetry breaking

Using all we know about electroweak symmetry breaking, ($v = 246$ GeV, 3 goldstone bosons, $M_W \sim M_Z$ (residual global SU(2) symmetry)), can write quite generally, to 1 loop (from the EWChL):

$$\begin{aligned} \mathcal{A}(s, t, u) = & \frac{s}{v^2} + \frac{4}{v^4} \left[2a_5(\mu)s^2 + a_4(\mu)(t^2 + u^2) + \frac{1}{(4\pi)^2} \frac{10s^2 + 13(t^2 + u^2)}{72} \right] \\ & - \frac{1}{96\pi^2 v^4} \left[t(s + 2t) \log\left(\frac{-t}{\mu^2}\right) + u(s + 2u) \log\left(\frac{-u}{\mu^2}\right) + 3s^2 \log\left(\frac{-s}{\mu^2}\right) \right] \end{aligned}$$

a_4 and a_5 parameterise our ignorance of the new physics (they come from the only dimension-4 terms we could add to the EWChL)

$$\mathcal{L}^{(4)} = a_4(\langle D_\mu U D^\nu U^\dagger \rangle)^2 + a_5(\langle D_\mu U D^\mu U^\dagger \rangle)^2$$

Experimental Aspects: Photons

- Backgrounds:
 - jet fragmenting into single hard π^0
 - Use high granularity strip and wire chambers in central calorimeter to separate π^0 from photon
 - New strip and wire chambers in forward calorimeter
 - Electrons where track is not found
 - Difficult in forward region where only Silicon (no drift chamber)
 - Developing robust and efficient algorithms
- Develop generic methods to estimate backgrounds:
 - Jet fake rate about 0.1-0.01% for developed cuts

